

PROBING THE LOW-REDSHIFT STAR FORMATION RATE AS A FUNCTION OF METALLICITY
THROUGH THE LOCAL ENVIRONMENTS OF TYPE II SUPERNOVAER. STOLL¹, J.L. PRIETO^{2,3}, K.Z. STANEK^{1,4}, R.W. POGGE^{1,4}*Draft version March 3, 2013*

ABSTRACT

Type II SNe can be used as a star formation tracer to probe the metallicity distribution of global low-redshift star formation. We present oxygen and iron abundance distributions of type II supernova progenitor regions that avoid many previous sources of bias, and can serve as a standard of comparison for properly observationally evaluating how different classes of supernovae depend on progenitor metallicity. In contrast to previous supernova host metallicity studies, this sample is homogeneous and is drawn from an areal rather than a targeted survey, so supernovae in the lowest-mass galaxies are not excluded. We spectroscopically measure the gas-phase oxygen abundance near a representative subsample of the hosts of type II supernovae from the first-year Palomar Transient Factory (PTF) supernova search. The median metallicity is $12+\log(\text{O}/\text{H}) = 8.65$ and the median host galaxy stellar mass from fits to SDSS photometry is $10^{9.9} M_{\odot}$. Though iron abundance is more central to the evolution of massive stars than oxygen abundance, it cannot be measured directly in extragalactic HII regions. Using the relationship between iron and oxygen abundances found for Milky Way disk, bulge, and halo stars, we can translate our distribution of type II SN environments as a function of oxygen abundance into an estimate of the iron abundance, and find the median $[\text{Fe}/\text{H}] = -0.60$.

Subject headings: (stars:) supernovae: general; galaxies: abundances; galaxies: dwarf

1. INTRODUCTION

The question of how different classes of supernovae (SNe) depend on progenitor metallicity has been limited by the lack of an unbiased standard of comparison. The metallicity distribution of galaxies is insufficient because core-collapse supernovae (CCSNe) trace star formation rather than stellar mass. Existing supernova host galaxy metallicity distributions are limited by heterogeneous supernova samples and supernova surveys that do not search in the faintest hosts. We will address this by creating a metallicity distribution of type II supernova progenitor regions that avoids many previous sources of bias.

The observational properties of CCSNe span a broad range of spectral types, luminosities, apparent kinetic energies, and other properties. Interpreting this diversity remains a fundamental theoretical and observational challenge, particularly as to how differences in the stellar progenitors of the SNe are related to the explosions. For example, the relative fractions of hydrogen-rich type II SNe and hydrogen-poor type Ib/c SNe can be predicted as a function of metallicity based on models for mass-loss from the progenitor stars (Eldridge et al. 2008; Georgy et al. 2009, 2012). Standard mass loss models for massive stars are based on line-driven winds (e.g. Kudritzki & Puls 2000); the efficiency of these winds depends on metallicity because metals, particularly iron, dominate the line opacities driving the winds (Vink & de Koter 2005). Furthermore, the explosion energy of normal type II SNe may depend on the progenitor metallicity (Kasen & Woosley 2009), and certain types of

SNe may occur only for low-metallicity progenitor stars (Ober et al. 1983; Heger & Woosley 2002; Langer et al. 2007).

Serendipitous observations of SN progenitor stars prior to explosion are profoundly useful for sorting out how the SN properties depend on the progenitor (e.g. Smartt 2009, and references therein). Unfortunately, observing or strongly constraining the properties of the progenitor star is only possible for nearby galaxies, leading to very small samples. This limits the utility of this technique for constraining the properties of subclasses of events that are rare and therefore observed mostly at large distances, such as extremely optically luminous CCSNe.

Observational techniques for addressing this question without pre-explosion data involve estimating the progenitor properties from the environments that remain behind. These techniques range from estimating progenitor age and mass from the degree of correlation with H α emission (Anderson & James 2008), to detailed characterization of resolved stellar populations near supernova explosion sites in nearby galaxies (Badenes et al. 2009; Murphy et al. 2011) to extrapolation of stellar population properties from galaxy photometry and spectroscopic observations (e.g. Kelly & Kirshner 2011).

Spectroscopic observations of H II regions near a supernova can be used to estimate the metallicity using strong-line oxygen abundance indicators. There are precision and accuracy limitations to strong-line abundance estimates, but more rigorous abundance measurements using faint auroral lines are too costly (or completely unfeasible) for statistical surveys of SN host metallicities.

The frequency of several classes of CCSN types have been found to vary with host metallicity. Prantzos & Boissier (2003) found that the ratio between type Ib/c and type II SNe declines with increasing host luminosity, and because of the galaxy lumi-

¹ Department of Astronomy, The Ohio State University

² Department of Astrophysical Sciences, Princeton University

³ Hubble and Carnegie-Princeton Fellow

⁴ Center for Cosmology and AstroParticle Physics, The Ohio State University

osity/metallicity relationship, they suggested this was probably a metallicity effect. This was confirmed and expanded upon by Prieto et al. (2008) in a subsequent study, which found that hosts of type Ib/c SNe are higher metallicity than hosts of type II and type Ia SNe based on spectroscopically measured metallicity. Stanek et al. (2006) found that type Ic SNe associated with nearby long gamma-ray bursts (GRBs) were in faint, metal-poor galaxies, proposing a progenitor metallicity cutoff above which GRBs do not occur, and Modjaz et al. (2008) found that type Ic SNe that were associated with GRBs were in more metal-poor regions than those that were not. Anderson et al. (2010) found that type Ib and type Ic SNe hosts have marginally higher metallicity than hosts of type II and type Ia SNe. The metallicity local to type Ic SNe without broad lines was found by Modjaz et al. (2011) to be on average higher than near type Ib SNe, regardless of which strong-line metallicity diagnostic was used, consistent with the results of Kelly & Kirshner (2011), though Anderson et al. (2010) disagree. Kelly & Kirshner (2011) found that although hosts of type Ib and type Ic SNe are higher in metallicity than hosts of type II SNe, hosts of broad-lined type Ic (Ic-BL) SNe are lower in metallicity.

Type II SNe which are abnormally optically luminous appear to occur more often in low-mass, low-luminosity galaxies (Neill et al. 2011). Spectroscopic abundance measurements of hosts of five such luminous CCSNe indicate this is likely due to metallicity, as shown by Stoll et al. (2011) (including data from Young et al. 2010; Kozłowski et al. 2010). Subsequent spectroscopic measurements of the host of the luminous SN 2008am (Chatzopoulos et al. 2011) and the luminous SN 2010ay (Prieto & Filippenko 2010; Modjaz et al. 2010; Sanders et al. 2011), and photometric limits on the hosts of the luminous SNe PS1-10awh and PS1-10ky (Chomiuk et al. 2011) reinforce this conclusion.

Many studies (e.g. Sanders et al. 2011; Stoll et al. 2011; Campisi et al. 2011; Vergani et al. 2011) compare host galaxies of SNe or GRBs to the overall galaxy population, which is a good way to put the host metallicity results in context. It is not, however, a secure way to evaluate whether metallicity is a key parameter governing whether a supernova has a given spectral type or luminosity. Supernovae trace star formation rather than overall stellar mass, and star formation is not evenly distributed among galaxies of a given mass. Recent results (Lara-López et al. 2010; Mannucci et al. 2010) show that the scatter in the galaxy mass-metallicity relationship is reduced by considering star formation as a third parameter, and that star formation rates (SFRs) are higher in lower metallicity galaxies at a given mass (but see also Yates et al. 2012).

Levesque et al. (2010) and Han et al. (2010) suggested that instead of a metallicity cutoff for GRBs there is a separate luminosity-metallicity relationship for GRB host galaxies offset to lower metallicity than the normal galaxy mass-metallicity relationship of Tremonti et al. (2004). (These results are consistent with a simple metallicity cutoff with the exception of a single high-mass GRB host galaxy that appears to be high metallicity.) This question of an offset in the mass-metallicity relationship has confused many subsequent discussions of a metallic-

ity cutoff.

Mannucci et al. (2011) notes that for galaxies at a given mass, lower metallicity galaxies have higher average star formation rates (Mannucci et al. 2010) and thus core-collapse events, which trace star formation, should have a mass-metallicity distribution shifted to slightly lower metallicity at a given mass. This effect is similar enough to the offset proposed by Levesque et al. (2010) and Han et al. (2010) that Mannucci et al. (2011) conclude that GRB hosts do not differ substantially from the typical galaxy population and therefore there is no metallicity dependence to GRB hosts. Many subsequent studies have claimed to disprove a metallicity connection for GRBs or luminous SNe by showing that the host galaxy metallicity is consistent with its mass and star formation rate according to the relationship between the three (Lara-López et al. 2010; Mannucci et al. 2010). While this is evidence against a distinct mass-metallicity relationship for the hosts of these SNe, it is not evidence against a *metallicity dependence*.

These investigations have not yet quantified the expected metallicity shift in the star formation rate due to this relationship. This shift can be quantified semi-analytically by convolving the galaxy mass function with the relationship between galaxy mass, metallicity, and star formation rate to find the overall distribution of star formation as a function of metallicity. Niino (2011) does so by comparing the observed metallicity distribution of GRB hosts to the metallicity distribution of star formation, calculated two different ways. First, calculated observationally from the stellar mass function, the galaxy M-SFR relation, and the galaxy mass-metallicity relation. Second, calculated using the relationship between galaxy mass, metallicity, and SFR defined by Mannucci et al. (2010), and assigning metallicities based on SFR as well as mass. He finds the difference between these two estimates is less than 0.5 dex in oxygen abundance on the KK04 scale. Regardless which method is used, he finds that the GRB host metallicity distribution is incompatible with the metallicity distribution of star formation unless the GRB fraction depends on metallicity. (This is not the primary result of that study, which examines the fact that galaxies do not have one single metallicity, but show an internal spread. Assuming a hypothetical transient phenomenon which has a strict cutoff metallicity above which it cannot occur, Niino (2011) shows that such a spread in internal galaxy metallicities would serve to widen the observed host metallicity distribution of that transient phenomenon.)

Only by comparing the metallicity distribution of a SN variety to the overall metallicity distribution of star formation can one rigorously test for a metallicity dependence. Our metallicity distribution of type II SN hosts can serve as a standard of comparison for evaluating how different classes of SNe depend on progenitor metallicity.

A problem for essentially all of these previous studies relating metallicity and SN properties is that they draw on heterogeneous SN samples. At present, the Palomar Transient Factory (Rau et al. 2009, PTF) appears to supply the closest approximation to an unbiased SN sample, in the sense that the SN selection is essentially independent of host galaxy properties. This would not be true, for example, of the Lick Observatory Supernova Search (LOSS) survey (Li et al. 2011), which explicitly

targets larger galaxies. In this paper we will focus on the 52 type II SNe found in the first year of PTF operations. Because some subtypes of CCSNe are known to have different distributions in host metallicity, we focus on type II SNe. We have measured metallicities for the environments of a representative subsample of 34 of these type II SNe, and present the resulting metallicity distribution.

This distribution probes the low-redshift star formation rate as a function of metallicity in an independent way from current methods relying on galaxy population statistics. This is an important distribution to characterize because in order to determine whether a massive star outcome has a metallicity dependence, we need to examine its frequency relative to the metallicity distribution of star formation, not to the metallicity distribution of existing stellar mass (the galaxy metallicity distribution).

We place the metallicity distribution of type II SNe environments in context by comparing it with previous supernova host studies (Prieto et al. 2008; Anderson et al. 2010; Kelly & Kirshner 2011), with the SDSS DR7 MPA/JHU value-added catalog (Kauffmann et al. 2003; Tremonti et al. 2004; Brinchmann et al. 2004; Salim et al. 2007), and with estimates from galaxy population statistics (Stanek et al. 2006). Noting that iron is more fundamental to stellar evolutionary outcomes than oxygen, we then translate our oxygen abundance distribution of type II SNe environments into an iron abundance distribution by using the observed relationship between oxygen and iron abundance in Milky Way galaxy, disk, and halo stellar abundances.

2. SPECTROSCOPIC OBSERVATIONS AND ANALYSIS

We drew our targets from the first-year of the Palomar Transient Factory (PTF) survey (Arcavi et al. 2010), an areal rather than a targeted survey, so supernovae in the lowest-mass galaxies are not excluded by selection. The sample selection for the survey is not yet published. There are 52 type II SNe in the full first-year PTF CCSN sample, of which we have measured spectroscopic metallicity determinations for a subsample of 34. This subsample is characteristic of the overall type II sample, as we show in §4.1.

We obtained host galaxy spectra of these SNe using the Ohio State Multi-Object Spectrograph (OSMOS, Martini et al. 2011; Stoll et al. 2010) on the 2.4-m Hiltner telescope, the Wide Field Reimaging CCD Camera (WFCCD) on the 2.5-m du Pont telescope, and the dual imaging spectrograph (DIS) on the 3.5-m Astrophysical Research Consortium telescope. We also use twelve archival spectra from SDSS DR7 (Abazajian et al. 2009; Uomoto et al. 1999; York et al. 2000; Gunn et al. 2006). The properties of the spectroscopic observations are summarized in Table 1. Images of nine representative type II hosts spanning the observed range of metallicity and galaxy mass are shown in Figure 1. We also measured spectroscopic metallicities for the hosts of three type Ib, two type IIb, three type Ic, and one type Ic-BL from the first-year PTF sample.

The new observations were made either at the supernova position or at a similar galactocentric radius to minimize any biases from metallicity gradients in the host galaxies. We include the angular distance from the host

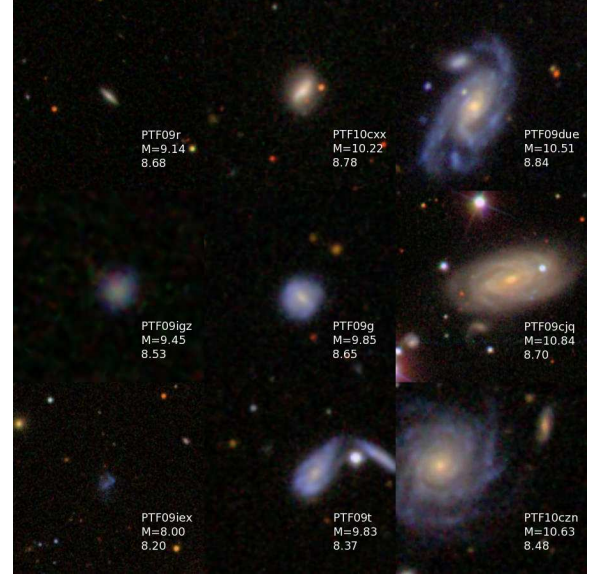


Figure 1. Nine type II SN hosts, spanning the metallicity and mass range, arranged so mass increases toward the right and oxygen abundance increases toward the top. Each panel is scaled to a physical size of 50 kpc ($H_0, \Omega_m, \Omega_\Lambda = 70, 0.3, 0.7$) and is centered on the position of the supernova. All images are from SDSS and were taken before the supernovae.

galaxy center to the supernova site in Table 2 for easy comparison to the seeing and to the spectroscopic aperture, listed in Table 1. We include the projected physical distance to facilitate future comparison to studies that use galactocentric spectra. For host galaxies with multiple SDSS spectra or with spectra from multiple sources, we fit a metallicity gradient where possible and provide the best fit metallicity at the galactocentric radius of the supernova progenitor; these are labeled as ‘grad’.

We primarily consider host metallicities determined with the N2 diagnostic of Pettini & Pagel (2004), which we directly measure for each of our targets. This diagnostic depends solely on $[\text{N II}]\lambda 6584/\text{H}\alpha\lambda 6563$, and is extremely insensitive to reddening, though it has a larger intrinsic scatter than other strong-line diagnostics based on the physical conditions of the H II regions. There are a number of techniques that are used to estimate the oxygen abundances of H II regions in star-forming galaxies, and a substantial literature discussing their various merits and drawbacks (e.g. Kewley & Ellison 2008, and references therein). A full recap of this is outside the scope of this paper, but we discuss the consequences of these uncertainties for our study in Section 4.6.

In Table 2 we list the metallicities of the progenitor regions of 34 type II SNe, three type Ib, two type IIb, three type Ic, and one type Ic-BL from the PTF first-year core-collapse sample. All subsequent analysis is of the type II hosts, for which we have good statistics. We do not include type IIb SNe in the type II sample because their spectral similarity to type Ib SNe at all but early times can lead to some typing issues, and because previous studies (e.g. Modjaz et al. 2011; Kelly & Kirshner 2011) considered them in the stripped-envelope subclass. We show the metallicity distribution of the type II hosts for several different strong-line metallicity diagnostics using the empirical conversions of Kewley & Ellison (2008)

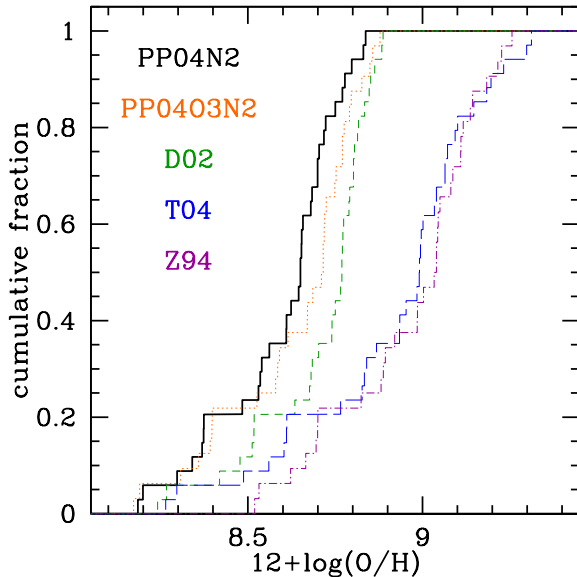


Figure 2. Cumulative distribution of local gas-phase oxygen abundances for type II SNe. As type II SNe trace young stellar populations, this traces the metallicity distribution of star formation at low redshift. The solid black distribution uses the N2 diagnostic of Pettini & Pagel (2004, PP04) we adopt as our standard. Subsequent figures only use these measurements. The other distributions show how the result would change for other strong-line metallicity diagnostics, based on the empirical conversions of Kewley & Ellison (2008). The dotted orange curve uses the PP04 O3N2 diagnostic, the short-dashed green curve uses Denicoló et al. (2002), the long-dashed blue curve uses Tremonti et al. (2004), the dot-dashed purple curve uses Zaritsky et al. (1994). We do not show conversions to the scales of Kobulnicky & Kewley (2004), McGaugh (1991), and Kewley & Dopita (2002), which require external branch information.

in Figure 2. In subsequent figures, we choose as our scale convention only the N2 diagnostic of Pettini & Pagel (2004).

3. CHARACTERIZING THE SPECTROSCOPIC SUBSAMPLE

To investigate whether we have acquired spectra of a representative subsample of the hosts of first-year PTF CCSNe, we compared the stellar mass and star formation rates of the hosts with and without metallicity estimates. We used SED models of the SDSS photometry of the hosts within the DR8 footprint to estimate the masses, SFR, and characteristic stellar ages. Of the 52 type II SNe in the full sample, 47 have SDSS photometry. We also analyzed the properties of the 19 non-type II PTF CCSN hosts that fell in the DR8 footprint, but we will restrict our comparisons with our spectroscopic sample of type II SNe to these 47 type II SNe to avoid any of the currently known selection effects with metallicity linked with supernova type (see §1).

3.1. Extracting fluxes from SDSS imaging

We obtained *ugriz* images for the 66 supernova fields in the SDSS Data Release 8 (Aihara et al. 2011). These images are fully calibrated in the SDSS natural system, which is close to the AB system, and sky-subtracted. We combined the most sensitive SDSS bands (*gri*) for each supernova field in order to make a deeper stacked

image that can be used to find all the galaxies and define their photometric apertures. We used these deeper stacked images as the reference image for source detection using SExtractor (Bertin & Arnouts 1996) and checked by eye the positions around each supernova in order to select the most likely host galaxy. We were able to assign likely host galaxies for 64/66 SNe. The two events without host galaxy detections, PTF09be and PTF09gyp, have sources that are $\gtrsim 13$ kpc (projected) from the positions of the SNe. We note that the host of PTF09gyp has a reported magnitude of $r = 21.75$ mag in Arcavi et al. (2010) from SDSS photometry, but we do not confirm this detection. After selecting the host galaxies in the stacked images, we used *imedit* in IRAF⁵ to mask nearby stars, which could contaminate the flux measurements, filling the masked regions with the local background. Finally, we ran SExtractor on the individual *ugriz* images using the apertures defined from the deeper stacked images to obtain total (AUTO) galaxy fluxes. We applied the small ($\lesssim 0.04$ mag) corrections derived in Kessler et al. (2009) to transform the SDSS fluxes to the AB system. The resulting coordinates and fluxes of the host galaxies are presented in Table 3, and absolute magnitudes are presented in Table 4. We include 3σ upper limits for the hosts of PTF09be and PTF09gyp, which were calculated assuming a circular aperture of radius $r = 5$ kpc at the distance of the SN.

3.2. Galaxy properties

We used the code for Fitting and Assessment of Synthetic Templates (FAST v0.9b, Kriek et al. 2009) to fit these host galaxy spectral energy distributions to estimate the stellar mass, star formation rates (SFRs), and characteristic ages. We chose the Bruzual & Charlot (2003) libraries, a Salpeter IMF, and Solar ($Z = 0.02$) metallicity to do the fits. We also assumed an exponentially declining SFR model with $\tau = 1$ Gyr for the star forming component of the model. The results are presented in Table 5.

Since the star-formation rates derived with FAST can be dependent on the assumed SFR model, we obtained an independent SFR estimate using the *u*-band luminosities of the galaxies. We used the results of Salim et al. (2007) for ~ 50000 SDSS galaxies with GALEX photometry to derive a relation between the absolute *u*-band magnitudes, corrected for intrinsic attenuation, and their derived SFRs. We obtain a linear relation fit between M_u and SFR (in M_\odot/yr) of the form $\log(\text{SFR}) = -0.36 \times M_u - 6.73$ (for a Salpeter IMF), valid for $2 > \log(\text{SFR}) > -2$ and $\log(\text{SFR}/M_\star) > -10.5$, with an rms scatter of 0.23 dex. We applied this relation to obtain SFRs for the supernova host galaxies, using the Low-Resolution Template code of Assef et al. (2008) to derive *K*-corrected *u*-band absolute magnitudes corrected for Galactic extinction. After further correcting these magnitudes by intrinsic attenuation using the values obtained with FAST and the Calzetti reddening law, we applied the linear relation derived from the Salim et al. (2007) data to estimate SFRs. These independent val-

⁵ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

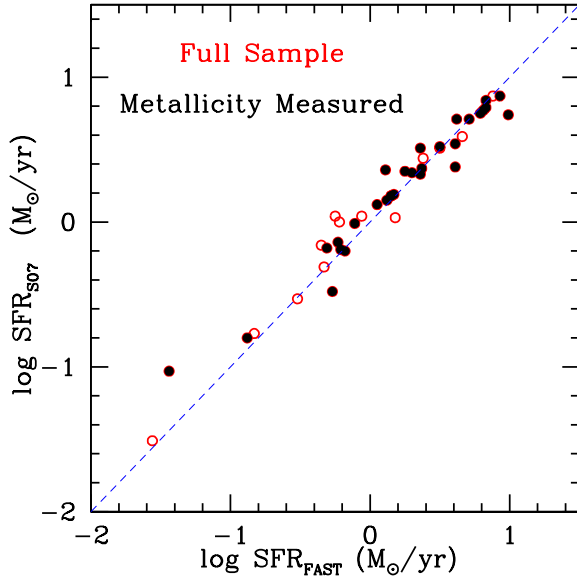


Figure 3. The two methods of estimating SFR are consistent. SFR estimates based on u-band photometry (Salim et al. 2007) are plotted against SFR estimates based on FAST for the full sample of PTF type II SN hosts (open red points) and the metallicity subsample (solid black points). The blue dashed line represents a 1:1 correspondence.

ues are presented in Table 5. The agreement with the SFRs derived by FAST is fairly good in general, with a Kolmogorov-Smirnov (K-S) test probability of 81% of the results of the two different methods being drawn from the same underlying distribution. The two SFR estimation methods are directly compared in Figure 3. The SFR calculated from the u-band luminosity with aperture corrections is more consistent with the method the MPA/JHU value-added catalog uses to determine star formation rates than the FAST template fitting.

4. DISCUSSION

This is the largest homogeneous sample of supernova host galaxy spectra metallicity measurements yet. Nevertheless, limited observing time made following up the entire PTF type II sample impractical, so we first consider whether our spectroscopic host sample is representative of the full sample, finding that it is. We then place the SN hosts in context by comparing their properties to those of galaxies in the MPA/JHU value-added catalog. While they are well-matched in galaxy mass and metallicity, the type II hosts appear to be biased toward higher star formation rates than the galaxies in the catalog. The metallicity distribution of these type II hosts is remarkably similar to that found by previous studies of hosts of type II SNe, despite their more inhomogeneous selection. Their metallicity distribution is also consistent with a distribution of star formation calculated from galaxy population statistics. We discuss how our study avoids some selection effects due to supernova type and host galaxy type that might influence the metallicity distribution. A key future use of the metallicity distribution of type II SNe we find here will be to evaluate possible metallicity dependence of other subclasses of CCSNe. We discuss the advantages and disadvantages of the metallicity diagnostic we choose for this study. Finally, we define

a relationship between oxygen and iron abundances, and convert our observed oxygen abundance distribution into an assumed iron abundance distribution, as iron is more important to the evolution of massive stars than oxygen.

4.1. How representative is the metallicity sample?

To investigate how representative the subsample for which we have spectra and metallicities is of the entire sample of PTF type II SN hosts we compared the distributions of the two samples in galaxy mass, characteristic stellar age, and star formation rate, using the 32 (47) hosts with (without) measured metallicities that also lie in the SDSS DR8 imaging footprint. Figures 4 and 5 show that the two sub-samples have essentially identical distributions in host mass (K-S probability 99.9%), age (57.8%), and SFR (64–74%, depending on the SFR estimation method).

We also investigated the effects of redshift on the completeness of the sample by dividing it into lower and higher redshift subsamples and comparing the properties of the two. In Figure 6 we show the metallicity distribution of these two subsamples. A K-S test indicates that the two have a 19% probability of being drawn from the same metallicity distribution, consistent at approximately 1σ . The hosts in the two redshift bins have essentially identical distributions in host mass (K-S probability 63%), age (91%), and SFR (91–99%, depending on the estimation method).

4.2. The type II metallicity sample in context

We next compare our sample to galaxy properties in the DR7 SDSS MPA/JHU value-added catalog for context (Kauffmann et al. 2003; Tremonti et al. 2004; Brinchmann et al. 2004; Salim et al. 2007). We compare to the subset of the DR7 objects which have redshifts within the range of our sample, successful estimates of the stellar mass and star formation rate, a $12+\log(\text{O}/\text{H})$ metallicity estimate, and an $[\text{N II}]\lambda 6584/\text{H}\alpha\lambda 6563$ flux ratio within the valid range for the PP04 N2 metallicity diagnostic. This last requirement has almost no effect, reducing the sample by only 0.7%. The strictest condition by far is the requirement of a valid Tremonti et al. (2004) metallicity estimate. Note that the galaxy properties in the MPA/JHU value-added catalog are a function of redshift because is not a volume-limited sample. The selection that defines the catalog is reflected in the properties of its constituents.

As shown in Figure 7, the SN hosts appear to trace the MPA/JHU sample well. They do not appear to be biased toward lower metallicities at a given mass (left panel) as a simplistic interpretation of the results of Mannucci et al. (2010) might suggest. It has been suggested that core-collapse SNe and GRBs may be less frequently observed in higher metallicity environments due to higher extinction (e.g. Maiolino et al. 2002; Mannucci et al. 2003; Cresci et al. 2007; Campisi et al. 2011), but this sample does not show evidence for such a bias. The SN hosts do, however, appear to be biased toward higher star formation rates⁶ (right panel) than the MPA/JHU galaxy sample, as would be expected if they do indeed trace star formation. They appear to well-sample the distribution

⁶ Here we use the SFR calculated from the u-band luminosity with aperture corrections.

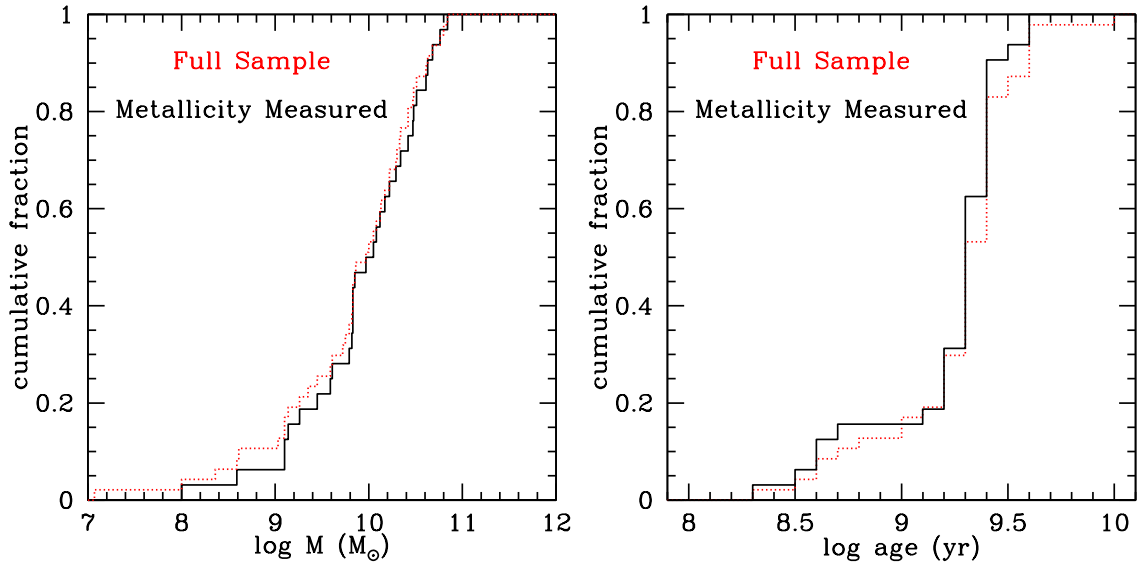


Figure 4. The distributions of the full PTF type II sample (dotted red) and those for which we obtained metallicities (solid black). Section 3.2 describes how the host properties were estimated. The subsample for which we have spectroscopic metallicity measurements is quite representative of the full sample, with K-S test probabilities of 99.9% (mass) and 57.8% (age) that they are drawn from the same distribution.

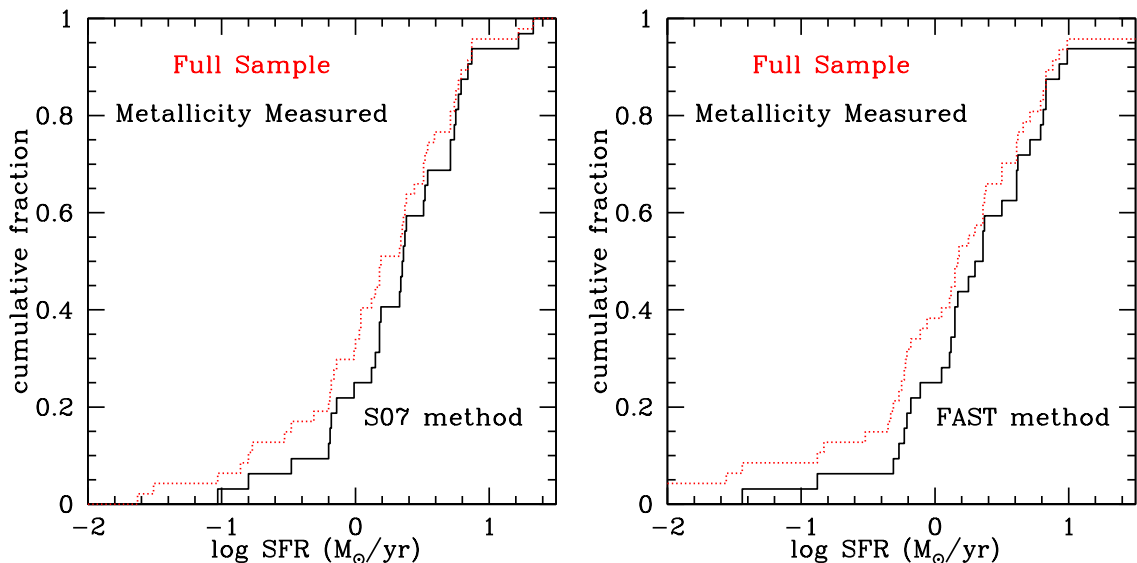


Figure 5. The subsample of type II hosts for which we have measured metallicities (solid black) is representative of the full sample of PTF type II SN hosts (dotted red) in SFR based on u-band photometry (Salim et al. 2007, left) and FAST (right).

of the MPA/JHU sample in galaxy mass and star formation rate, as shown in Figure 8.

4.3. Comparing with other SNe host samples

Work on the metallicity distribution of supernova hosts by Prieto et al. (2008) and Kelly & Kirshner (2011) looked at overall galaxy metallicity with serendipitous SDSS spectra, without isolating the SN site. Studies by Anderson et al. (2010) tried to measure abundances at the SN site or at a similar galactocentric radius, as we have done in this study. These previous studies had uniform spectroscopy but the source SN samples were heterogeneous, including SNe discovered in a wide variety

of ways with very different selection effects. Our source SN sample is homogeneous, from a single survey with uniform selection. The source survey is areal rather than galaxy-targeted, which enables the detection of events in the lowest-mass galaxies, removing or at least mitigating a possible bias towards high metallicity environments which we expect exists in prior supernova host samples. We do not attempt to define a volume-limited supernova sample here. Rather, we point out that this existing sample represents a substantial step forward for this purpose from previous similar samples.

Kelly & Kirshner (2011) used abundances following Tremonti et al. (2004) and the O3N2 method of

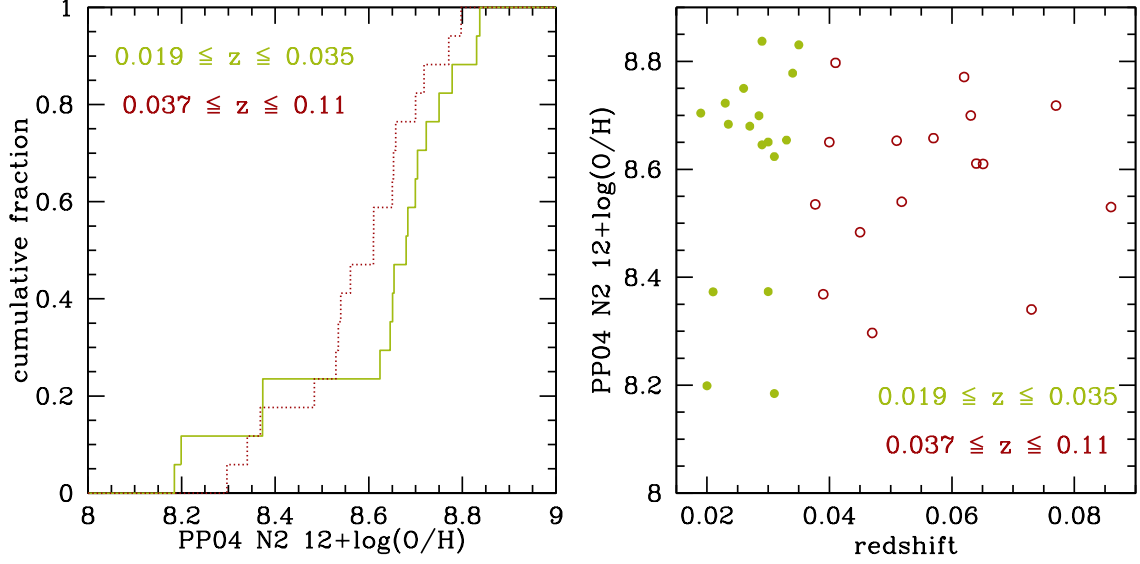


Figure 6. The metallicity distribution of the type II hosts separated into two bins in redshift of seventeen hosts each (left). The green solid (red dotted) line is the lower (higher) redshift half of the sample, $0.019 \leq z \leq 0.035$ ($0.037 \leq z \leq 0.11$). On the right, the distribution is expanded and metallicities are plotted against redshift. Here the lower redshift half of the sample is green solid points, and the higher redshift is red open points. A K-S test shows the two are consistent with being drawn from the same distribution in metallicity at the 19% level. There do not appear to be any major selection effects with redshift.

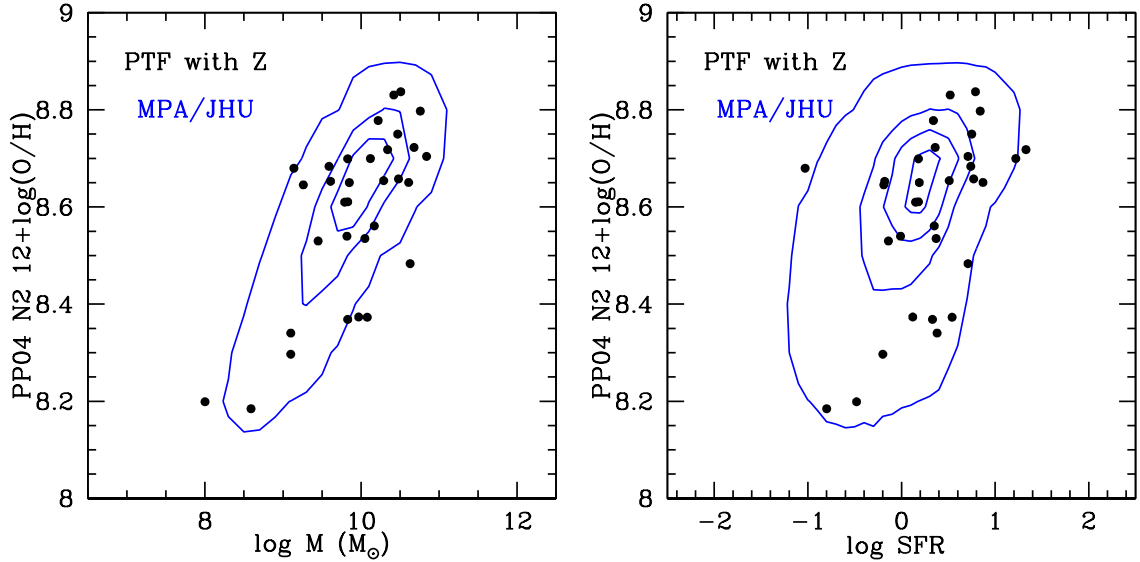


Figure 7. Measured host metallicities (black points) as a function of galaxy mass (left) or SFR (right), overlaid on the distribution in the MPA/JHU value-added catalog in the same redshift range (blue contours). Our hosts are slightly offset to higher star formation rates, as we would expect if type II SNe trace star formation.

Pettini & Pagel (2004). In this paper we use the N2 method of Pettini & Pagel (2004), so we must convert these to a common scale. The valid range of the conversion defined by Kewley & Ellison (2008) from the scale of the O3N2 method to the scale of the N2 method does not span the abundances here, so we convert from the Tremonti et al. (2004) abundances instead. Prieto et al. (2008) also uses abundances from the method of Tremonti et al. (2004). The conversion defined by Kewley & Ellison (2008) from the scale of Tremonti et al. (2004) to the N2 method of

Pettini & Pagel (2004) turns over at low metallicities, and does not match the reverse conversion. To ensure monotonicity, we define an ad hoc conversion by fitting to the reverse conversion defined by Kewley & Ellison (2008) (see Appendix). This conversion is a fit to a fit rather than a fit to data, but it achieves two purposes: avoiding a turnover at low metallicity and matching the inverse conversion from PP04 N2 to T04. We use this conversion everywhere in this paper when converting from the scale of the T04 diagnostic to the scale of the PP04 N2 method. Approximately 9% of the Prieto et al.

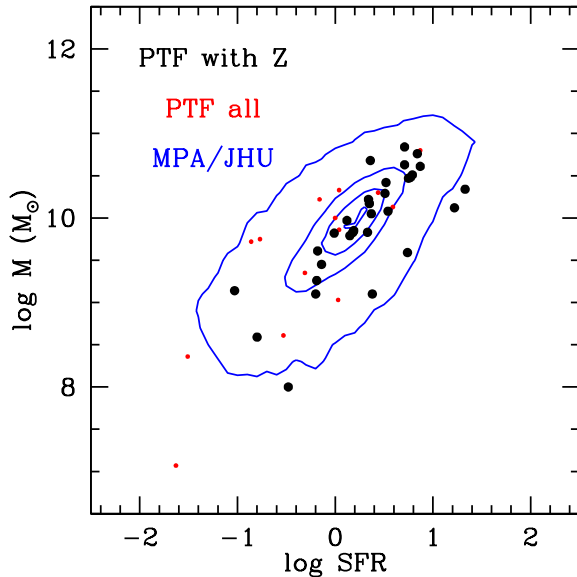


Figure 8. Host mass and SFR for our type II SN hosts with Z measurements (large black points), all first-year PTF type II SNe hosts in the SDSS photometric footprint (small red points), overlaid on the distribution in the MPA/JHU catalog (blue contours).

(2008) sample have T04 metallicities above or below the valid conversion range defined by Kewley & Ellison (2008). Because our conversion is well-behaved at low metallicity, we convert the entire sample instead of excluding that 9%. The decision to include these hosts with the lowest and highest metallicity is not highly consequential; the distribution of the full sample with our conversion is consistent (at a K-S probability of 66%) with the remaining 91% converted using the method of Kewley & Ellison (2008).

We compare our type II host metallicity distribution with those found by Prieto et al. (2008), Anderson et al. (2010) and Kelly & Kirshner (2011) in Figure 9. The K-S test probabilities that our type II sample could be selected from the same underlying distribution as those in the earlier studies are 87%, 45%, and 11%, respectively. The agreement of our SN metallicity distribution with the results of these prior studies is striking, given the different sample selection.

4.4. Comparing with SFR metallicity distributions from galaxy population statistics

One semi-observational way of determining the global distribution of star formation as a function of metallicity is to combine the observed galaxy mass function, the observed mean star formation rate as a function of galaxy mass, and the observed galaxy mass-metallicity relationship. In Figure 10 we plot our distribution against one such determination based on galaxy population statistics (Stanek et al. 2006). Each of the three observed relationships that are inputs to this alternate method of finding the metallicity distribution of star formation has its own set of selection effects. Potential biases or redshift-dependent effects in the samples used to define the relation could offset the distribution in metallicity. The width of the distribution may be misrepresented by using a mean relationship to translate from one prop-

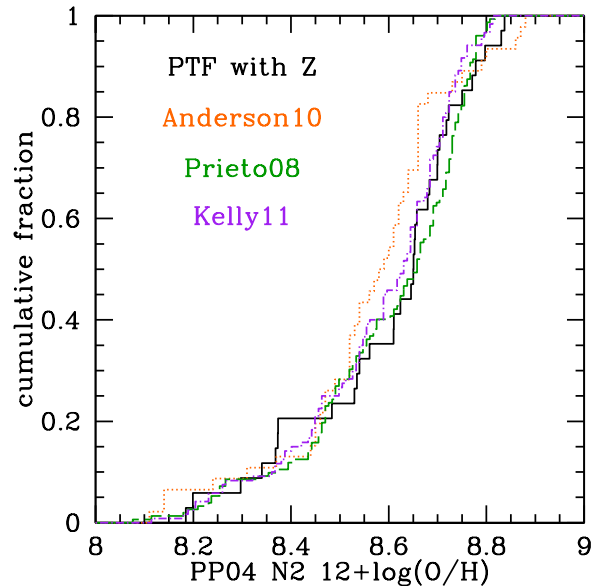


Figure 9. Distribution of local gas-phase oxygen abundance of our sample of type II SNe (black solid line) compared with existing SN host metallicity samples. The dotted orange curve shows the heterogeneous type II subsample of Anderson et al. (2010). The K-S probability of this sample being drawn from the same underlying distribution as our PTF type II sample is 11%. Similarly, the green long-dash curve shows the distribution of type II, IIP, and IIn SNe from Prieto et al. (2008) (K-S probability 87%) and the purple dash-dot curve shows the type II sample from Kelly & Kirshner (2011) (K-S probability 45%). In the latter two cases we converted their T04 scale metallicity to the PP04N2 scale using the conversion given in the Appendix.

erty into another, such as the mass-metallicity relationship (Tremonti et al. 2004) or the three-way relationship between mass, metallicity, and star formation rate (Lara-López et al. 2010; Mannucci et al. 2010), because the scatter around that relationship may not be carried through to the final distribution.

Core-collapse SNe, as the deaths of massive, young stars, are a relatively good tracer of SFR. Using the metallicity distribution of a uniform sample of type II SN sites to approximate the metallicity distribution of star formation, as we have done, should have almost completely independent selection effects from methods relying on galaxy population statistics.

4.5. Selection effects

One of the primary potential sources of incompleteness in using type II SNe environments to trace the metallicity distribution of global star formation will of course be the selection of the sample of type II SNe. An ideal sample for this purpose would be a complete, volume-limited sample, monitoring a fixed region of sky for a fixed period of time, and then eliminating events outside the complete sample. Up until very recently, most supernova surveys have monitored large, luminous galaxies rather than regions of the sky, a methodology which has the potential to miss any SNe in the very lowest end of the galaxy luminosity function. The Palomar Transient Factory survey is areal, which removes the potential bias against extremely low-mass host galaxies of targeted surveys. Because the survey selection is not yet published, however, we are unable to correct for any biases in our

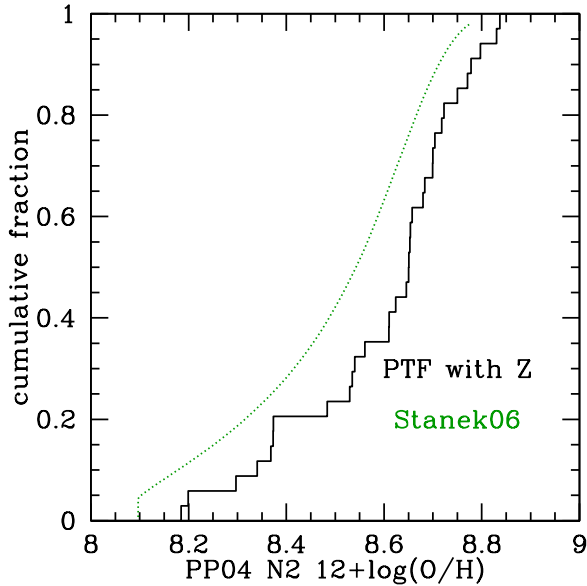


Figure 10. The distribution of star formation as a function of metallicity from galaxy population statistics from Stanek et al. (2006) (green dotted line) to our distribution of site metallicities of type II CCSNe (black solid line).

source sample to get a distribution for a volume-limited sample. With the current rapid growth in depth and breadth of supernova surveys, there is great potential for this method of determining the metallicity distribution of star formation.

Another potential source of bias for this method is any dependence of the likelihood of a massive star resulting in a type II SN on metallicity. Type II-P SNe make up around 70% of all type II SNe in the LOSS survey, which focuses on relatively luminous galaxies (Li et al. 2011). The frequency of type II SNe has not yet been found to depend on metallicity, unlike type Ib and Ic SNe. We examine only the distribution of type II hosts, for which we have good statistics. The type II distribution is consistent with the distribution of the nine type Ib/Ic/IIb hosts we have measured with a K-S probability of 23%, and the distribution of the hosts of all CCSNe we have measured (including all the type II hosts) is consistent with the type II distribution with a K-S probability of 99%, shown in Figure 11 (left). Completeness corrections to translate between type II hosts and all CCSN hosts may depend slightly on metallicity.

Several types of CCSNe are known to vary in frequency with metallicity, as discussed in §1. Our very small sample of spectroscopic metallicity measurements of hosts of type IIb/Ib/Ic SNe is statistically consistent with these previous results (Modjaz et al. 2011; Anderson et al. 2010; Kelly & Kirshner 2011), but not at very high significance level. Using the host galaxy properties we fit from SDSS photometry gives us slightly better statistics, shown in Figure 11 (right). The relative distributions of type II, IIb, Ib, Ic, and Ic-BL in photometrically calculated host mass are consistent with the recent results of Kelly & Kirshner (2011). The overrepresentation of types IIb and Ic-BL in low-mass hosts is consistent with the results of Arcavi et al. (2010) based on host galaxy luminosities.

4.6. Strong-line metallicity diagnostics

There is a substantial literature on the merits and disadvantages of each commonly-used method of determining metallicities based on fluxes of strong emission lines (e.g. Berg et al. 2011; Kewley & Ellison 2008, and references therein). These methods all rely on simplifying assumptions about the H II regions being examined: uniformity of electron density, cooling dominated by oxygen (implying that other cooling species have abundances that vary in lockstep with oxygen), and ionization-bounded H II regions (e.g. Pagel et al. 1979). The methods can be classified into rough categories: direct methods, which rely on estimates of the electron temperature and require measurements of faint auroral lines such as $[\text{O III}]\lambda 4363\text{\AA}$, empirical (e.g. Pettini & Pagel 2004), theoretical (e.g. Kobulnicky & Kewley 2004), and a combination of empirical and theoretical (e.g. Denicoló et al. 2002). All these methods are based on high S/N measurements of the line ratios of different combinations of emission lines from ions present in the optical region of the spectrum ($\simeq 3700 - 6800\text{\AA}$: $[\text{O II}]$, $[\text{O III}]$, $[\text{N II}]$, $[\text{S II}]$, $\text{H}\alpha$, and $\text{H}\beta$).

The slope and intercept of the galaxy mass-metallicity relationship is different for each diagnostic (Kewley & Ellison 2008), which is a relatively straightforward way to demonstrate that they are not all directly measuring some platonic ideal of a fundamental oxygen abundance measurement. (This problem is independent of the separate question of the exact value of the solar oxygen abundance, which also affects how measured gas-phase abundances map to stellar abundances.) Instead, each technique measures something that correlates well with oxygen abundance, but does not directly map to it. The simplifying assumptions that allow us to use each strong-line indicator to estimate oxygen abundance are not perfect for all H II regions. Rigorously selecting the best diagnostic for a given situation requires better data than are achievable for distant and faint targets, and doing a case-by-case selection of strong-line method on insufficient data would introduce its own biases.

The primary advantage of the strong-line techniques is that they are possible with fewer photons, and are therefore feasible to perform on large samples for good population statistics. Given the scale differences between methods, however, it is crucially important to ensure that all metallicities one is comparing are on the same scale. Where possible, we do this by natively determining the metallicities in a common scale. Where impossible, we convert a metallicity determined on another scale using the empirical conversions of Kewley & Ellison (2008) (but see Appendix A). We emphasize that any meaningful conclusion should not be affected by a change in the metallicity calibration.

The primary scale we choose for this study is the N2 diagnostic of Pettini & Pagel (2004), which depends solely on $[\text{N II}]\lambda 6584/\text{H}\alpha\lambda 6563$. A disadvantage of the method is that it shows a larger dispersion from the average fit than for most other strong line diagnostics. There are a number of advantages of this diagnostic, however. The ratio is very insensitive to reddening due to the close wavelength proximity of the lines. It is monotonic with oxygen abundance. It depends on lines with relatively high fluxes in star forming environments, which means

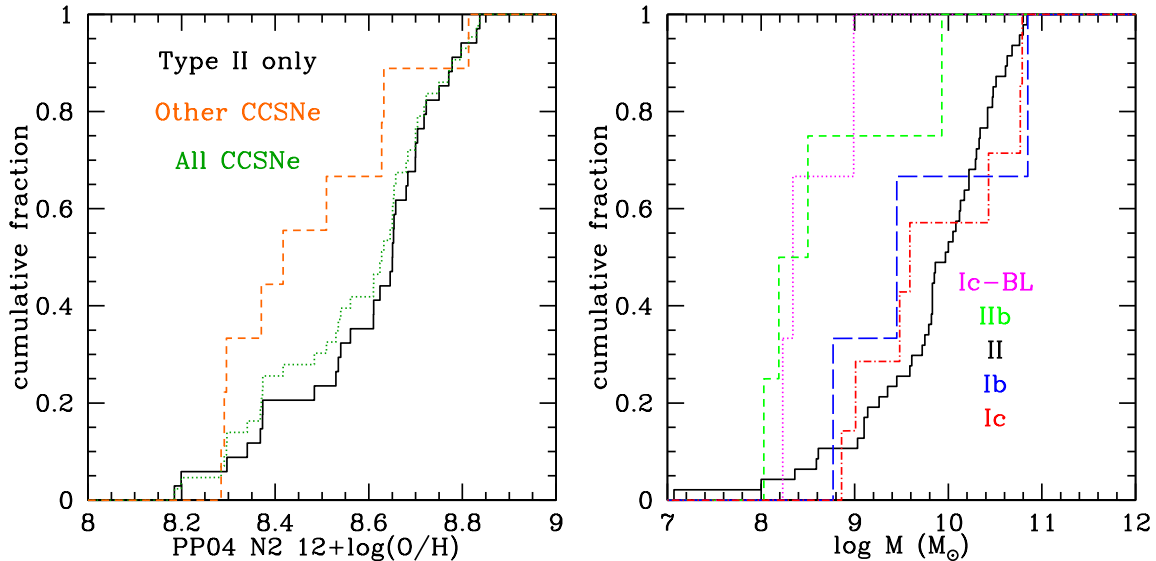


Figure 11. The metallicity distribution (left) of type II SN hosts (solid black), all other CCSN hosts (dashed orange) and all CCSN hosts in Table 2 (dotted green). With this small sample of other subtypes, the type II distribution is statistically consistent with the other CCSNe (K-S probability 23%) and with all CCSNe (K-S probability 99%). Increasing the sample size, the distribution in photometrically calculated host galaxy mass (right) of type II SN hosts (black solid), Ic-BL (pink dotted), IIb (green short-dashed), Ib (blue long-dashed), and Ic (red dot-dashed).

that good metallicity estimates can be achieved at relatively low observational expense. Yin et al. (2007) find it is more consistent with T_e methods than the O3N2 diagnostic of Pettini & Pagel (2004). Bresolin et al. (2009) compare a variety of strong-line abundance estimators and find that PP04 N2 is the closest match in both slope and normalization to the oxygen abundance gradient in NGC 300 measured with stellar metallicity (blue supergiants).

4.7. Iron abundances

Iron is more fundamentally important than oxygen for the late-stage evolution of massive stars, because iron provides much of the opacity for radiation-driven stellar winds (Pauldrach et al. 1986; Vink & de Koter 2005, e.g.). Unfortunately, gas-phase iron abundances are difficult to measure, and the fraction of iron depleted onto grains is highly variable. Even within our own galaxy, measuring iron abundances is challenging (e.g. Rodríguez 2002; Jensen & Snow 2007; Okada et al. 2008). We measure gas-phase oxygen abundances instead as a proxy for metallicity because it is observationally feasible.

Gas-phase oxygen abundance estimated with PP04 N2 is well correlated with stellar oxygen abundances (Bresolin et al. 2009). Our gas-phase oxygen abundances are thus a good proxy for the stellar oxygen abundances of the progenitors of these CCSNe. We can use our oxygen abundances to estimate the more physically important (for massive star evolution) iron abundances. This mapping is not linear because iron abundance varies more steeply than oxygen abundance in stars. At low metallicity, α -elements like oxygen are enhanced relative to iron compared to the solar mixture. In the galactic disk and halo, at $[\text{Fe}/\text{H}] > -1$, $[\text{O}/\text{Fe}]$ is approximately inversely proportional to $[\text{Fe}/\text{H}]$, while below $[\text{Fe}/\text{H}] = -1$, $[\text{O}/\text{Fe}]$ may flatten out at a constant (and lower) relative iron abundance (e.g. Tinsley 1979; McWilliam

1997; Johnson et al. 2007; Epstein et al. 2010) (but see e.g. Israelian et al. 1998).

To estimate the conversion, we compared $[\text{O}/\text{Fe}]$ to $[\text{Fe}/\text{H}]$ over a wide range in metallicities using stellar abundance measurements from the Milky Way bulge, disk, and halo (Fulbright et al. 2007; Rich et al. 2007; Rich & Origlia 2005; Lecureur et al. 2007; Reddy et al. 2003, 2006; Bensby et al. 2004; Chen et al. 2003). Noting that $[\text{O}/\text{H}] = [\text{O}/\text{Fe}] + [\text{Fe}/\text{H}]$, we fit the relationship between $[\text{O}/\text{H}]$ and $[\text{Fe}/\text{H}]$ with an unweighted linear fit, as seen in Figure 12, and find

$$[\text{Fe}/\text{H}] = c_1 + c_2([\text{O}/\text{H}]), \quad (1)$$

where $c_1 = -0.34 \pm 0.01$ and $c_2 = 1.25 \pm 0.05$. Although the eye is drawn to a steeper trend at higher metallicity than the formal fit shown, this is an illusion based on relatively few points; the fit is driven to be flatter by a dense concentration of points with $-0.2 < [\text{O}/\text{H}] < 0.2$ and $-0.5 < [\text{Fe}/\text{H}] < 0$. The relationship does not differ substantially between bulge stars (shown in red) and halo and disk stars (shown in blue). If $[\text{O}/\text{Fe}]$ flattens out below $[\text{Fe}/\text{H}] = -1$, the linear relationship we choose to fit may not be ideal. We would expect to find a slightly steeper relationship were we to exclude points below $[\text{Fe}/\text{H}] = -1$, which would mean that type II SN progenitors in low oxygen abundance host regions have even lower iron abundance than we find here. Because there is finite scatter in the measured relationship, however, imposing a strict cut at $[\text{Fe}/\text{H}] = -1$ actually drives the fit to be slightly flatter by biasing the points with lowest $[\text{O}/\text{H}]$ to higher $[\text{Fe}/\text{H}]$.

Applying the fit to a direct conversion between $12+\log(\text{O}/\text{H})$ and $[\text{Fe}/\text{H}]$ requires assuming a solar oxygen abundance because stellar abundances are measured relative to solar, while gas phase abundances are absolute (at least to the accuracy of the assumptions for a given strong line method). There is currently some dis-

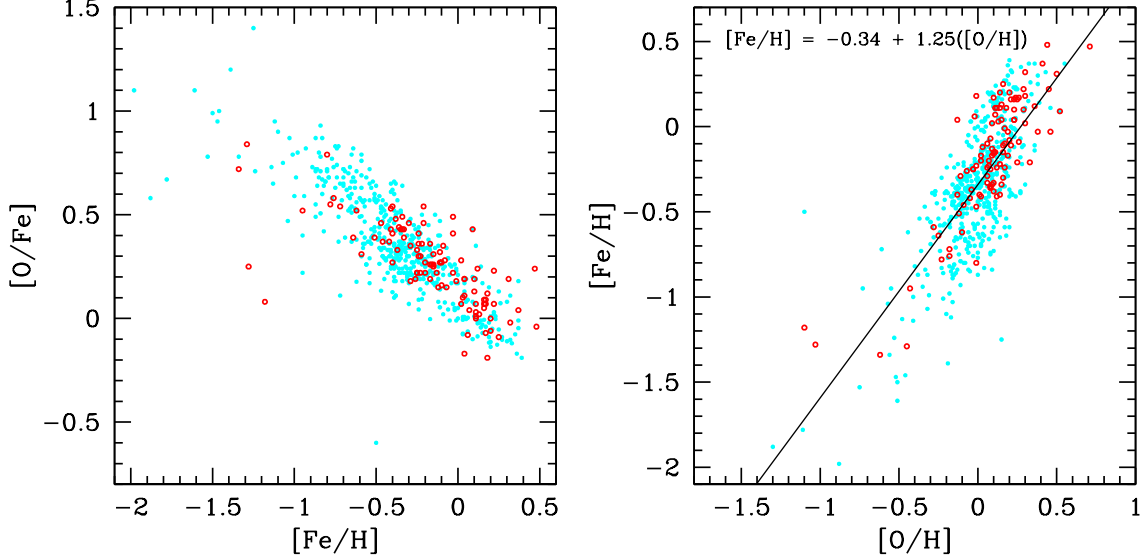


Figure 12. To translate oxygen abundances into iron abundances, we fit a linear relation (black) to the iron and oxygen abundances of Milky Way bulge, disk, and halo stars. At low metallicity, α -elements like oxygen are enhanced relative to iron compared to the solar mixture. On the left is the well-known relationship between $[O/Fe]$ and $[Fe/H]$. The red open points are iron and oxygen abundances of bulge stars (Fulbright et al. 2007; Lecureur et al. 2007; Rich & Origlia 2005; Rich et al. 2007). The blue solid points are halo and disk stars (Bensby et al. 2004; Chen et al. 2003; Reddy et al. 2003, 2006). On the right we express this in terms of $[O/H]$ and $[Fe/H]$ and fit the relation. Although the eye is drawn to a steeper trend at higher metallicity than the formal fit, this is an illusion based on relatively few points; the fit is driven to be flatter by a dense concentration of points with $-0.2 < [O/H] < 0.2$ and $-0.5 < [Fe/H] < 0$. Equation 2 can be used to conservatively convert a measured gas-phase oxygen abundance to iron abundance for a given solar oxygen abundance (modulo the uncertainties of equating gas-phase strong-line oxygen abundance indicators to stellar oxygen abundances).

pute over the solar abundance because results from atmospheric and interiors methods differ. For a given solar oxygen abundance O_{\odot} ,

$$[Fe/H] = c_1 - c_2 O_{\odot} + c_2(12 + \log(O/H)). \quad (2)$$

Using a solar oxygen abundance of $O_{\odot} = 8.86$ (Delahaye & Pinsonneault 2006), the conversion is $[Fe/H] = -11.4 + 1.25(12 + \log(O/H))$, while using $O_{\odot} = 8.69$ (Asplund et al. 2009), the conversion is $[Fe/H] = -11.2 + 1.25(12 + \log(O/H))$.

One more assumption must be made; we must convert strong-line oxygen abundance to stellar oxygen abundance. Which strong line indicator maps most precisely to stellar oxygen abundance across a wide variety H II region conditions in a wide variety of galaxy types is not well known. For the purpose of this paper, however, we assume that PP04 N2 maps precisely to stellar oxygen abundances (as motivated by the results of Bresolin et al. 2009), and make no correction to either slope or zero point.

We apply this fit to transform our oxygen abundance distribution of type II progenitors into an iron abundance distribution, shown in Figure 13. The median value of $[Fe/H]$ is -0.60 using the solar value of Delahaye & Pinsonneault (2006). If another solar oxygen abundance O_{\odot} is assumed, the calculated iron value shifts by

$$c_2(8.86 - O_{\odot}), \quad (3)$$

so using $O_{\odot} = 8.69$ (Asplund et al. 2009), for example, the median value of $[Fe/H]$ is -0.39 .

A striking outcome of this translation is that all of the type II SN progenitors in this sample appear to have sub-solar iron abundances. Although this is notable, it is not

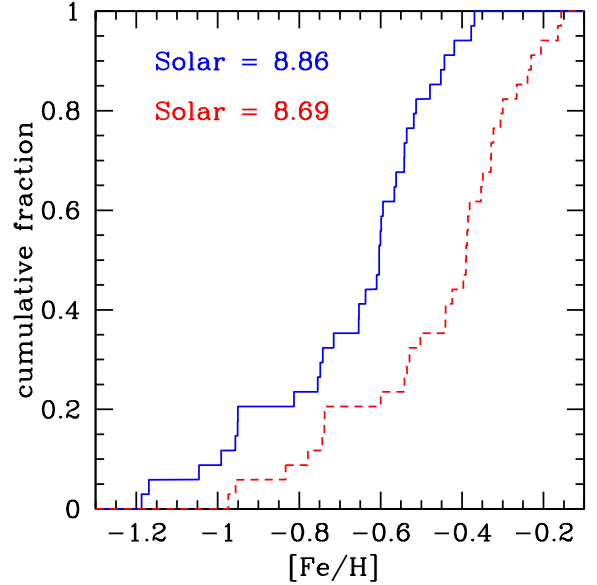


Figure 13. The estimated $[Fe/H]$ distribution of the type II SN sites. The blue solid line is the distribution assuming the solar oxygen abundance is 8.86 (Delahaye & Pinsonneault 2006), and the red dashed line is the distribution assuming the solar oxygen abundance is 8.69 (Asplund et al. 2009).

entirely surprising; the sun is more enhanced in iron than most Milky Way stars at its oxygen abundance, and all of the host galaxies in this sample are smaller than the Milky Way. Were we to assume that $[O/Fe]$ flattens out below $[Fe/H] = -1$ instead of remaining linear, the slope we fit would be steeper and the iron abundances we find

here would be even lower.

The type II progenitors all have iron abundances greater than $[\text{Fe}/\text{H}] = -1.5$, putting them squarely in the regime where winds are primarily driven by iron opacity. For the most metal-poor stars ($Z/Z_{\odot} < 10^{-3}$), non-iron elements such as carbon dominate the radiative driving (Vink & de Koter 2005), but in the metallicity range of these type II SN progenitors, iron abundance should still be the dominant factor which determines wind strength and mass loss.

5. CONCLUSIONS

The primary result of this paper is a new progenitor region metallicity distribution for a uniform sample of type II SNe. Understanding this distribution is important for understanding any possible metallicity dependences of different types of events associated with massive stars, and it can serve as a probe of the metallicity distribution of star formation.

The host galaxies of our type II sample appear to well trace galaxies from the MPA/JHU value-added catalog in mass and metallicity, showing a slight bias towards higher star formation rates.

We find a similarity between the existing host metallicity distributions for heterogeneous type II supernova samples and the metallicity distribution we derive. Because the existing host metallicity distributions are based on supernova samples that are drawn predominantly from galaxy-targeted supernova searches, one might naively expect these previous distributions might be biased towards higher mass and therefore higher metallicity galaxies. We do not find such a trend.

Comparing to the metallicity distribution of star formation rather than to the metallicity distribution of galaxies as a function of mass is the correct way to evaluate a possible metallicity dependence of a transient population associated with young stars. We point out that using CCSNe to trace star formation leads to an almost entirely independent way of probing the metallicity distribution of star formation from methods involving galaxy population statistics, and we compare the metallicity distribution we derive to one of these.

Finally, we present our host metallicity distribution in terms of iron abundance, by converting our oxygen abundance distribution to an iron abundance distribution using the α/Fe relationship observed in Milky Way bulge, disk, and halo stars, noting that iron is more important than oxygen for the late-stage evolution of massive stars.

We find that $-1.2 < [\text{Fe}/\text{H}] < 0$ for these type II SN progenitors. Though all have sub-solar iron abundance, none are metal-poor enough that elements other than iron will dominate the wind-driving opacity of the progenitor star.

Future improvements to this estimate of the metallicity distribution of type II SNe can be made by performing completeness corrections for any selection or followup biases in the source survey. If the peak luminosity of type II SNe is found to depend on host galaxy metallicity, there may also be Malmquist-like biases to correct.

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APPENDIX

METALLICITY CONVERSIONS

It is well known that the various strong-line oxygen abundance estimators have different scales and zero-points. (For excellent pictorial representations of this, see Figure 2 of Kewley & Ellison (2008) or Figure 12 of Bresolin et al. (2009).) Because of these differences in scale and zero-point, it is critically necessary to put different estimates on a common scale before comparing abundances. Kewley & Ellison (2008) determined empirical conversions between many of the commonly used scales by fitting the trend defined by performing a given two diagnostics on a large sample of high S/N galaxy spectra from SDSS. While these conversions have been very useful to the community, there can be problems using them at very low metallicity. The forward and reverse conversions between two methods are not always consistent, as can be seen in Figure 14. The problem appears to be a consequence of the interaction of the vast statistical weight of the abundant high-metallicity galaxies and the third-order polynomials (which are not precisely invertible) in which the conversions are expressed. The high-metallicity end is tightly pinned, allowing low-metallicity end of the third-order polynomial to shift between the forward and reverse conversions.

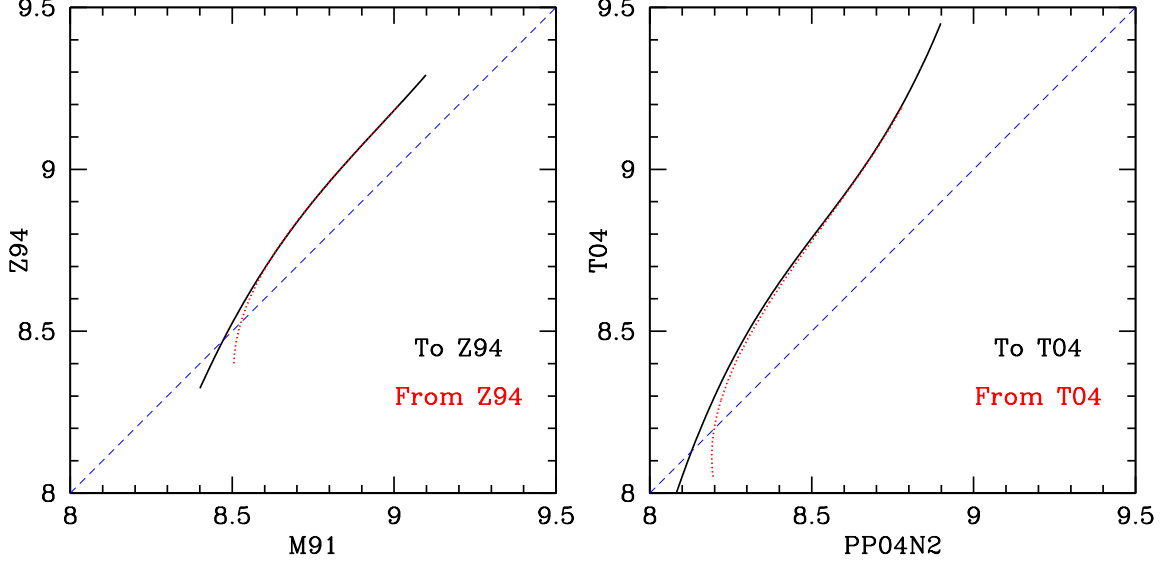


Figure 14. Forward and reverse conversion over the entire valid conversion ranges between the metallicity scale of Zaritsky et al. (1994) and McGaugh (1991) (left) and Tremonti et al. (2004) and Pettini & Pagel (2004) (right). To Z94 and T04 is the red dotted line, while from Z94 and T04 is the black solid line. The blue dashed line would represent a conversion between two exactly equivalent metallicity scales. The scales are the same as those in Figure 3 in Kewley & Ellison (2008).

For the purposes of this paper, we need to avoid the double-value of the T04 to PP04N2 conversion at low metallicities. We do so by defining an ad hoc conversion from T04 to PP04N2, as shown in Figure 15. This conversion is a third-order polynomial fit to the conversion from T04 to PP04N2 given in Kewley & Ellison (2008). This fit is defined by

$$y = a + bx + cx^2 + dx^3, \quad (\text{A1})$$

where $y = 12 + \log(\text{O}/\text{H})_{\text{PP04N2}}$, $x = 12 + \log(\text{O}/\text{H})_{\text{T04}}$, $a = 178.248$, $b = -59.2077$, $c = 6.80078$, and $d = -0.257326$. Note that this is a fit to a fit rather than a fit to data. We define it solely for the purposes of avoiding a turnover at low metallicity and matching the inverse conversion from PP04N2 to T04.

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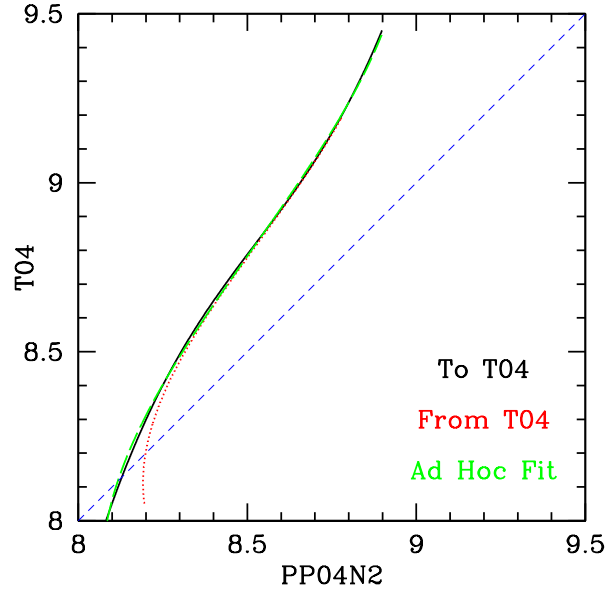


Figure 15. Forward and reverse conversion over the entire valid conversion ranges between the metallicity scale of Tremonti et al. (2004) and the N2 diagnostic of Pettini & Pagel (2004). The scales are the same as those in Figure 3 in Kewley & Ellison (2008). The black solid line is the conversion defined by Kewley & Ellison (2008) from the N2 diagnostic of Pettini & Pagel (2004) to the metallicity scale of Tremonti et al. (2004). The red dotted line is the conversion defined by Kewley & Ellison (2008) from the metallicity scale of Tremonti et al. (2004) to the N2 diagnostic of Pettini & Pagel (2004). The blue dashed line marks where a 1:1 correspondence between the two diagnostics would fall. The green long-dashed line shows our fit to the forward conversion, which we use in this paper to convert from T04 to PP04N2 in order to ensure monotonic behavior at low metallicities.

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Table 1
Observation properties

Telescope	Instrument	slit width (arcsec)	ruling (lines/mm)	λ coverage (Å)	resolution (Å)
APO	DIS	1.5	B400/R300 (gratings)	3500–9800	7
du Pont	WFCCD	1.7	400 (blue grism)	3700–9200	7
Hiltner	OSMOS	1.2	704 (grism)	3960–6870	3
SDSS	fiber spectrograph	3 (dia)	B640/R440 (grisms)	3800–9200	3

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Table 2
Measured host metallicities

SN Name	z	type	$12+\log(\text{O}/\text{H})$ (PP04N2)	[Fe/H] (8.86)	SN radius ^{a,b} (arcsec)	SN radius ^c (kpc)	Source
PTF09awk	0.0620	Ib	8.42	-0.90	0.10	0.11	SDSS
PTF09bce	0.0230	II	8.72	-0.51	5.93	2.76	OSMOS
PTF09bcl	0.0620	II	8.77	-0.45	APO
PTF09bgf	0.0310	II	8.18	-1.19	1.17	0.72	duPont
PTF09cjq	0.0190	II	8.70	-0.54	14.24	5.49	APO
PTF09cu	0.0570	II	8.66	-0.59	9.14	10.10	APO
PTF09dah	0.0238	IIb	8.37	-0.95	2.32	1.12	duPont
PTF09dfk	0.0160	Ib	8.30	-1.05	1.25	0.41	duPont
PTF09dra	0.0770	II	8.72	-0.52	3.63	5.29	SDSS
PTF09due	0.0290	II	8.84	-0.37	9.91	5.76	APOgrad
PTF09dxv	0.0330	IIb	8.63	-0.63	6.26	4.12	duPont
PTF09ebq	0.0235	II	8.68	-0.56	0.69	0.33	duPont
PTF09ecm	0.0285	II	8.70	-0.54	5.17	2.96	duPont
PTF09fbf	0.0210	II	8.37	-0.95	4.55	1.93	duPont
PTF09fma	0.0310	II	8.62	-0.64	duPont
PTF09fmk	0.0631	II	8.70	-0.54	3.68	4.47	duPont
PTF09fqa	0.0300	II	8.37	-0.95	10.76	6.46	duPont
PTF09fsr	0.0079	Ib	8.63	-0.63	64.61	10.55	duPont
PTF09g	0.0400	II	8.65	-0.60	3.83	3.03	SDSS
PTF09gof	0.1030	II	8.56	-0.72	1.90	3.59	duPont
PTF09iex	0.0200	II	8.20	-1.17	4.43	1.79	duPont
PTF09ige	0.0640	II	8.61	-0.65	5.10	6.28	SDSS
PTF09igz	0.0860	II	8.53	-0.75	1.69	2.72	APO
PTF09ism	0.0290	II	8.65	-0.61	7.47	4.34	SDSS
PTF09q	0.0900	Ic	8.81	-0.40	2.88	4.84	SDSS
PTF09r	0.0270	II	8.68	-0.57	0.79	0.43	OSMOS
PTF09sh	0.0377	II	8.54	-0.75	9.73	7.27	APO
PTF09sk	0.0355	Ic-BL	8.28	-1.06	2.77	1.95	SDSS
PTF09t	0.0390	II	8.37	-0.96	5.84	4.51	duPont
PTF09tm	0.0350	II	8.83	-0.38	3.64	2.53	SDSS
PTF09uj	0.0651	II	8.61	-0.65	2.72	3.40	SDSS
PTF10bau	0.0260	II	8.75	-0.48	6.18	3.23	grad
PTF10bgl	0.0300	II	8.65	-0.60	8.19	4.92	OSMgrad
PTF10bhu	0.0360	Ic	8.51	-0.78	1.62	1.16	SDSS
PTF10bip	0.0510	Ic	8.29	-1.05	1.24	1.23	duPont
PTF10con	0.0330	II	8.65	-0.60	1.72	1.13	duPont
PTF10cqh	0.0410	II	8.80	-0.42	9.17	7.43	duPont
PTF10cwx	0.0730	II	8.34	-0.99	2.56	3.55	duPont
PTF10cxq	0.0470	II	8.30	-1.05	1.53	1.41	duPont
PTF10cxx	0.0340	II	8.78	-0.44	1.84	1.24	SDSS
PTF10czn	0.0450	II	8.48	-0.81	14.98	13.25	duPont
PTF10hv	0.0518	II	8.54	-0.74	5.59	5.65	SDSS
PTF10s	0.0510	II	8.65	-0.60	1.05	1.04	SDSS

^a SN radius from the center of the galaxy. For the 12 targets for which we use archival SDSS spectra (indicated), this is the distance between the SN location and the fiber center, rather than from the center of the galaxy; a difference of half an arcsecond or less in all cases.

^b PTF09bcl and PTF09fma are outside the SDSS photometry, so we do not determine the coordinates of their host galaxy centers.

^c Projected physical radius calculated (Wright 2006) assuming $H_0 = 70$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

Table 3
Host properties measured from SDSS photometry

SN (PTF)	type	SN RA (J2000.0)	SN Dec (J2000.0)	Gal RA (J2000.0)	Gal Dec (J2000.0)	z	f_u (Jy)	f_g (Jy)	f_r (Jy)	f_i (Jy)	f_z (Jy)
09aux	Ic/Ia	16:09:15.84	+29:17:36.7	16:09:15.851	+29:17:37.09	0.047	1.42E-04±8.5E-06	5.87E-04±1.2E-05	1.15E-03±2.3E-05	1.57E-03±3.2E-05	1.99E-03±6.3E-05
09awx	Ib	13:37:56.36	+22:55:04.8	13:37:56.354	+22:55:04.82	0.062	8.41E-05±5.4E-06	1.96E-04±4.2E-06	2.72E-04±5.8E-06	3.58E-04±7.9E-06	3.89E-04±1.6E-05
09axc	II	14:53:13.06	+22:14:32.2	14:53:13.066	+22:14:32.22	0.115	2.51E-05±3.0E-06	9.85E-05±2.2E-06	1.88E-04±4.0E-06	2.40E-04±5.3E-06	2.78E-04±1.4E-05
09axi	II	14:12:40.82	+31:04:03.3	14:12:40.942	+31:04:03.51	0.064	3.67E-05±6.1E-06	1.09E-04±2.9E-06	1.79E-04±4.9E-06	1.90E-04±6.4E-06	1.74E-04±1.9E-05
09bce	II	16:35:17.66	+55:37:59.1	16:35:18.117	+55:38:03.60	0.023	1.02E-03±5.2E-05	4.05E-03±8.3E-05	8.23E-03±1.7E-04	1.20E-02±2.4E-04	1.55E-02±4.7E-04
09bgi	II	14:41:38.28	+19:21:43.8	14:41:38.351	+19:21:43.21	0.031	5.69E-05±5.3E-06	1.29E-04±3.1E-06	1.65E-04±4.2E-06	1.89E-04±5.8E-06	2.08E-04±1.6E-05
09bwf	II	15:05:02.04	+48:40:01.9	15:05:02.037	+48:40:03.22	0.150	1.85E-06±1.8E-06	1.35E-05±1.1E-06	2.80E-05±1.5E-06	3.52E-05±2.5E-06	3.54E-05±7.6E-06
09cjq	II	21:16:28.48	-00:49:39.7	21:16:27.580	-00:49:35.16	0.019	2.97E-03±1.5E-04	1.05E-02±2.1E-04	2.10E-02±4.2E-04	2.96E-02±6.0E-04	3.93E-02±1.2E-03
09ctc	II	11:42:13.80	+10:38:53.9	11:42:13.837	+10:38:53.86	0.150	1.03E-05±2.5E-06	2.68E-05±1.2E-06	5.51E-05±2.2E-06	7.46E-05±3.5E-06	9.48E-05±1.1E-05
09cuu	II	13:15:23.14	+46:25:08.6	13:15:23.892	+46:25:13.40	0.057	3.85E-04±2.0E-05	1.05E-03±2.2E-05	1.77E-03±3.6E-05	2.38E-03±4.9E-05	2.83E-03±9.3E-05
09cvi	II	21:47:09.80	+08:18:35.6	21:47:09.984	+08:18:35.58	0.030	-1.11E-06±1.2E-06	4.06E-06±4.3E-07	4.63E-06±6.9E-07	4.97E-06±1.1E-06	9.74E-06±3.9E-06
09dah	IIb	22:45:17.05	+21:49:15.2	22:45:17.115	+21:49:17.34	0.024	1.80E-04±1.3E-05	3.79E-04±8.2E-06	5.11E-04±1.2E-05	6.63E-04±1.6E-05	7.64E-04±4.0E-05
09dfk	Ib	23:09:13.42	+07:48:15.4	23:09:13.471	+07:48:16.39	0.016	1.28E-04±7.9E-06	3.53E-04±7.5E-06	5.40E-04±1.1E-05	6.87E-04±1.5E-05	8.28E-04±3.2E-05
09djl	II	16:33:55.94	+30:14:16.3	16:33:55.969	+30:14:16.65	0.184	4.05E-06±2.1E-06	1.76E-05±8.0E-07	4.63E-05±1.4E-06	5.80E-05±2.2E-06	8.44E-05±9.8E-06
09dra	II	15:48:11.47	+41:13:28.2	15:48:11.297	+41:13:31.76	0.077	2.40E-04±1.5E-05	5.98E-04±1.3E-05	9.95E-04±2.1E-05	1.34E-03±2.9E-05	1.63E-03±5.9E-05
09dru	II	16:26:52.36	+51:33:23.9	16:26:53.240	+51:33:18.35	0.029	2.35E-03±1.2E-04	6.12E-03±1.3E-04	9.42E-03±1.9E-04	1.17E-02±2.4E-04	1.41E-02±4.3E-04
09dxv	IIb	23:08:34.73	+18:56:13.7	23:08:34.828	+18:56:19.80	0.033	3.99E-04±2.6E-05	1.17E-03±2.4E-05	1.94E-03±4.0E-05	2.77E-03±5.9E-05	3.55E-03±1.3E-04
09dzt	Ic	16:03:04.20	+21:01:47.2	16:03:03.823	+21:01:47.28	0.087	9.55E-05±9.2E-06	2.00E-04±4.9E-06	3.32E-04±8.7E-06	4.26E-04±1.3E-05	5.39E-04±4.2E-05
09ebq	II	00:14:01.69	+29:25:58.5	00:14:01.743	+29:25:58.47	0.024	5.79E-04±2.9E-05	1.44E-03±2.9E-05	2.40E-03±4.8E-05	3.15E-03±6.5E-05	4.01E-03±1.3E-04
09ecm	II	01:06:43.16	-06:22:40.9	01:06:43.123	-06:22:46.04	0.029	3.60E-04±2.4E-05	1.08E-03±2.3E-05	1.83E-03±3.8E-05	2.26E-03±4.8E-05	2.86E-03±1.0E-04
09ejz	Ic/Ia	00:55:07.29	-06:57:05.4	00:55:07.230	-06:57:04.82	0.110	5.63E-05±8.0E-06	1.86E-04±4.4E-06	4.32E-04±9.5E-06	6.28E-04±1.4E-05	8.24E-04±3.4E-05
09fae	IIb	17:26:20.33	+72:56:30.6	17:26:20.127	+72:56:28.74	0.067	2.23E-05±3.3E-06	3.59E-05±1.3E-06	3.76E-05±1.9E-06	4.74E-05±2.9E-06	8.00E-05±1.1E-05
09fbf	II	21:20:38.44	+01:02:52.9	21:20:38.208	+01:02:49.97	0.021	1.59E-03±8.1E-05	4.36E-03±9.0E-05	6.76E-03±1.4E-04	8.65E-03±1.8E-04	1.06E-02±3.3E-04
09fmk	II	23:57:46.19	+11:58:45.3	23:57:46.435	+11:58:44.53	0.063	1.65E-04±1.3E-05	4.44E-04±9.6E-06	7.74E-04±1.7E-05	1.21E-03±2.7E-05	1.40E-03±6.1E-05
09foy	II	23:17:10.58	+17:15:03.2	23:17:10.983	+17:15:04.12	0.060	1.99E-04±1.5E-05	5.79E-04±1.2E-05	9.82E-04±2.1E-05	1.34E-03±2.9E-05	1.50E-03±6.9E-05
09fqd	II	22:25:32.33	+18:59:41.4	22:25:33.064	+18:59:44.12	0.030	4.48E-04±2.7E-05	1.30E-03±2.7E-05	2.11E-03±4.4E-05	2.71E-03±5.7E-05	3.16E-03±1.1E-04
09fsr	Ib	23:04:52.98	+12:19:59.0	23:04:56.569	+12:19:21.47	0.008	1.61E-02±7.8E-04	6.23E-02±1.3E-03	1.24E-01±2.5E-03	1.73E-01±3.5E-03	2.13E-01±6.5E-03
09g	II	15:16:31.48	+54:27:34.7	15:16:31.418	+54:27:31.04	0.040	4.12E-04±2.1E-05	9.85E-04±2.0E-05	1.40E-03±2.9E-05	1.66E-03±3.4E-05	1.87E-03±6.7E-05
09gof	II	01:22:25.60	+03:38:08.4	01:22:25.476	+03:38:08.80	0.103	7.57E-05±8.2E-06	1.91E-04±4.5E-06	3.21E-04±7.5E-06	3.74E-04±1.0E-05	4.07E-04±2.8E-05
09gtt	II	02:20:37.70	+02:24:13.2	02:20:37.291	+02:24:24.30	0.041	4.74E-05±9.5E-06	1.39E-04±4.0E-06	1.78E-04±5.9E-06	2.73E-04±9.8E-06	2.85E-04±4.0E-05
09hdo	II	00:15:23.20	+30:43:19.3	00:15:22.815	+30:43:16.29	0.047	4.55E-04±2.4E-05	1.59E-03±3.3E-05	3.17E-03±6.4E-05	4.60E-03±9.4E-05	6.01E-03±1.9E-04
09hgz	II	11:50:57.74	+21:11:49.4	11:50:56.789	+21:11:50.06	0.028	3.64E-04±2.1E-05	1.38E-03±2.9E-05	2.97E-03±6.0E-05	4.45E-03±9.1E-05	6.25E-03±1.9E-04
09iex	II	12:02:46.86	+02:24:06.8	12:02:46.955	+02:24:02.61	0.020	8.43E-05±9.2E-06	1.59E-04±4.6E-06	1.94E-04±6.7E-06	2.28E-04±1.0E-05	3.01E-04±3.9E-05
09ige	II	08:55:34.24	+32:39:57.0	08:55:34.126	+32:40:01.34	0.064	1.39E-04±8.1E-06	3.49E-04±7.4E-06	4.98E-04±1.1E-05	6.26E-04±1.4E-05	6.35E-04±2.7E-05
09igz	II	08:53:56.70	+33:40:11.5	08:53:56.582	+33:40:10.68	0.086	3.04E-05±4.1E-06	7.07E-05±2.0E-06	1.04E-04±3.4E-06	1.29E-04±5.0E-06	1.42E-04±1.6E-05
09ism	II	11:44:35.87	+10:12:43.7	11:44:35.370	+10:12:46.55	0.029	1.98E-04±1.5E-05	4.85E-04±1.1E-05	7.06E-04±1.6E-05	8.73E-04±2.2E-05	9.28E-04±6.2E-05
09ps	Ic	16:14:08.62	+55:41:41.4	16:14:08.619	+55:41:41.78	0.106	2.18E-05±3.0E-06	4.35E-05±1.2E-06	6.19E-05±1.8E-06	7.92E-05±2.6E-06	6.72E-05±1.1E-05
09q	Ic	12:24:50.11	+08:25:58.8	12:24:50.022	+08:26:01.27	0.090	1.49E-04±1.1E-05	4.47E-04±9.6E-06	8.69E-04±1.8E-05	1.24E-03±2.6E-05	1.51E-03±5.2E-05
09r	II	14:18:58.63	+35:23:16.0	14:18:58.607	+35:23:15.26	0.027	4.01E-05±4.0E-06	1.37E-04±3.1E-06	2.54E-04±5.5E-06	3.32E-04±7.6E-06	3.98E-04±1.9E-05
09sh	II	16:13:58.08	+39:31:58.1	16:13:58.581	+39:31:50.29	0.038	6.53E-04±3.6E-05	1.46E-03±3.0E-05	2.34E-03±4.8E-05	3.04E-03±6.4E-05	2.83E-03±1.2E-04
09sk	Ic-BL	13:30:51.15	+30:20:04.9	13:30:51.179	+30:20:02.22	0.035	1.15E-04±6.7E-06	2.52E-04±5.6E-06	3.19E-04±6.9E-06	3.87E-04±9.1E-06	4.14E-04±1.9E-05
09t	II	14:15:43.29	+16:11:59.1	14:15:42.905	+16:12:00.93	0.039	5.39E-04±2.8E-05	1.24E-03±2.5E-05	1.67E-03±3.4E-05	1.99E-03±4.2E-05	2.14E-03±7.8E-05
09tm	II	13:46:55.94	+61:33:15.6	13:46:55.509	+61:33:17.33	0.035	4.21E-04±2.1E-05	1.41E-03±2.9E-05	2.68E-03±5.4E-05	3.76E-03±7.7E-05	4.84E-03±1.5E-04
09uj	II	14:20:11.15	+53:33:41.0	14:20:10.883	+53:33:42.11	0.065	1.14E-04±8.0E-06	2.86E-04±6.3E-06	4.33E-04±9.5E-06	5.28E-04±1.2E-05	5.38E-04±2.8E-05
10bau	II	09:16:21.29	+17:43:40.2	09:16:21.696	+17:43:38.08	0.026	2.47E-03±1.2E-04	6.20E-03±1.3E-04	1.02E-02±2.0E-04	1.28E-02±2.6E-04	1.56E-02±4.8E-04
10bfz	Ic-BL	12:54:41.27	+15:24:17.0	12:54:41.278	+15:24:16.42	0.150	1.80E-06±1.1E-06	4.07E-06±4.7E-07	6.37E-06±7.6E-07	4.20E-06±1.4E-06	1.20E-06±5.1E-06
10bgl	II	10:19:04.70	+46:27:23.3	10:19:05.166	+46:27:16.67	0.030	3.40E-03±1.6E-04	8.80E-03±1.8E-04	1.27E-02±2.6E-04	1.57E-02±3.2E-04	1.77E-02±5.4E-04
10bhu	Ic	12:55:28.44	+53:34:28.7	12:55:28.353	+53:34:30.63	0.036	2.17E-04±1.3E-05	5.53E-04±1.2E-05	8.10E-04±1.7E-05	9.83E-04±2.2E-05	1.17E-03±4.5E-05
10bip	Ic	12:34:10.52	+08:21:48.5	12:34:10.493	+08:21:49.67	0.051	2.75E-05±3.5E-06	9.00E-05±2.2E-06	1.16E-04±3.0E-06	1.46E-04±4.1E-06	1.74E-04±1.2E-05
10bzf	Ic-BL	11:44:02.99	+55:41:27.6	11:44:02.964	+55:41:22.55	0.050	3.89E-05±4.7E-06	5.33E-05±2.1E-06	8.66E-05±3.0E-06	1.09E-04±4.5E-06	1.37E-04±1.6E-05
10cd	II	03:00:32.93	+36:15:25.4	03:00:33.086	+36:15:25.02	0.045	2.11E-05±5.1E-06	5.21E-05±2.1E-06	9.28E-05±3.7E-06	8.22E-05±5.4E-06	1.02E-04±1.9E-05
10con	II	16:11:39.09	+00:52:33.3	16:11:39.154	+00:52:31.87	0.033	2.36E-04±2.2E-05	6.06E-04±1.4E-05	1.61E-03±3.5E-05	3.58E-03±7.5E-05	2.85E-03±1.1E-04
10cqf	II	16:10:37.60	-01:43:00.7	16:10:36.992	-01:43:01.65	0.041	5.53E-04±2.9E-05	1.98E-03±4.1E-05	3.91E-03±7.9E-05	5.67E-03±1.2E-04	7.45E-03±2.3E-04
10cwz	II	12:33:16.53	-00:03:10.6	12:33:16.405	-00:03:12.34	0.073	4.72E-05±4.0E-06	9.72E-05±2.6E-06	1.23E-04±3.7E-06	1.60E-04±5.3E-06	1.73E-04±1.7E-05
10cxq	II	13:48:19.32	+13:28:58.8	13:48:19.317	+13:28:57.27	0.047	1.03E-04±6.6E-06	2.23E-04±4.9E-06	2.77E-04±6.4E-06	3.22E-04±8.3E-06	3.25E-04±2.1E-05
10cxs	II	14:47:27.78	+01:55:03.8	14:47:27.701	+01:55:05.28	0.034	2.79E-04±1.5E-05	9.62E-04±2.0E-05	1.81E-03±3.7E-05	2.48E-03±5.1E-05	3.31E-03±1.1E-04
10czn	II	14:51:16.23	+15:26:43.6	14:51:17.242	+15:26:46.79	0.045	8.36E-04±4.4E-05	2.63E-03±5.4E-05	4.19E-03±8.5E-05	5.38E-03±1.1E-04	6.08E-03±2.0E-04
10dk	II	05:08:21.54	+00:12:42.9	05:08:21.597	+00:12:42.28	0.074	1.11E-06±2.0E-06	5.16E-06±6.5E-07	9.23E-06±1.1E-06	9.73E-06±1.7E-06	9.92E-06±7.6E-06
10dvb	II	17:16:12.25	+31:47:36.0	17:16:10.672	+31:47:32.32	0.023	1.81E-03±8.8E-05	4.49E-03±9.2E-05	7.00E-03±1.4E-04	8.64E-03±1.8E-04	1.06E-02±3.2E-04
10hvf	II	14:03:56.18	+54:27:31.1	14:03:56.535	+54:27:27.21	0.052	1.51E-04±1.0E-05	4.23E-04±9.2E-06	5.92E-04±1.3E-05	7.55E-04±1.7E-05	8.11E-04±3.7E-05
10in	IIb	07:50:01.24	+33:06:23.8	07:50:00.984	+33:06:27.99	0.070	2.64E-06±1.8E-06	7.66E-06±7.3E-07	9.70E-06±1.3E-06	1.63E-05±1.8E-06	1.16E-05±6.

Table 4
Host properties measured from SDSS photometry

SN Name	μ^a	M_u^b	M_g^b	M_r^b	M_i^b	M_z^b	M_B^b
PTF09aux	36.60	-18.43	-19.85	-20.49	-20.79	-21.03	-19.48
PTF09awk	37.22	-18.37	-19.18	-19.50	-19.72	-19.84	-18.90
PTF09axc	38.64	-18.70	-20.07	-20.59	-20.80	-20.94	-19.75
PTF09axi	37.29	-17.55	-18.60	-19.07	-19.11	-19.02	-18.35
PTF09bce	35.01	-18.76	-20.22	-20.95	-21.34	-21.62	-19.85
PTF09bgf	35.67	-16.39	-17.15	-17.38	-17.50	-17.59	-16.91
PTF09bw	39.27	-16.47	-18.58	-19.11	-19.32	-19.32	-18.25
PTF09cjv	34.58	-19.76	-21.03	-21.70	-22.01	-22.29	-20.67
PTF09ct	39.27	-18.35	-19.38	-19.90	-20.17	-20.42	-19.07
PTF09cu	37.03	-19.80	-20.82	-21.33	-21.61	-21.81	-20.51
PTF09cvi	35.59	99.99	-13.51	-13.56	-13.58	-14.27	-13.18
PTF09dah	35.08	-17.17	-17.85	-18.12	-18.35	-18.48	-17.60
PTF09dfk	34.21	-15.90	-16.89	-17.29	-17.51	-17.68	-16.60
PTF09djl	39.75	-17.92	-19.52	-20.20	-20.39	-20.79	-19.20
PTF09dra	37.71	-19.98	-20.93	-21.41	-21.68	-21.91	-20.63
PTF09due	35.52	-20.23	-21.18	-21.62	-21.83	-22.03	-20.90
PTF09dxv	35.81	-19.38	-20.24	-20.61	-20.86	-21.04	-19.97
PTF09dzt	38.00	-19.62	-20.30	-20.72	-20.85	-21.09	-20.05
PTF09ebq	35.05	-18.32	-19.23	-19.74	-19.99	-20.23	-18.93
PTF09ecm	35.48	-18.82	-19.74	-20.15	-20.27	-20.45	-19.47
PTF09ejz	38.54	-19.72	-20.92	-21.59	-21.88	-22.13	-20.57
PTF09fae	37.40	-17.07	-17.52	-17.59	-17.68	-18.29	-17.29
PTF09fbf	34.80	-19.36	-20.30	-20.69	-20.90	-21.08	-20.02
PTF09fmk	37.26	-19.49	-20.40	-20.95	-21.24	-21.41	-20.08
PTF09foy	37.15	-19.39	-20.41	-20.89	-21.16	-21.28	-20.11
PTF09fqa	35.59	-18.66	-19.69	-20.15	-20.38	-20.52	-19.39
PTF09fsr	32.67	-19.89	-21.19	-21.81	-22.09	-22.25	-20.84
PTF09g	36.23	-19.07	-19.90	-20.25	-20.41	-20.54	-19.65
PTF09gof	38.38	-19.56	-20.43	-20.85	-20.97	-21.06	-20.18
PTF09gtt	36.29	-16.92	-17.92	-18.14	-18.56	-18.59	-17.62
PTF09hdo	36.60	-19.83	-21.06	-21.69	-22.02	-22.29	-20.71
PTF09hgz	35.44	-18.21	-19.62	-20.37	-20.77	-21.12	-19.25
PTF09iex	34.70	-15.79	-16.40	-16.60	-16.74	-17.03	-16.16
PTF09ige	37.29	-19.07	-19.91	-20.22	-20.43	-20.44	-19.66
PTF09igz	37.97	-18.09	-18.89	-19.21	-19.38	-19.49	-18.63
PTF09ism	35.52	-17.82	-18.62	-18.95	-19.12	-19.15	-18.37
PTF09ps	38.46	-18.09	-18.79	-19.11	-19.25	-19.14	-18.54
PTF09q	38.07	-19.92	-21.07	-21.67	-21.98	-22.21	-20.73
PTF09r	35.36	-15.63	-16.90	-17.53	-17.80	-18.00	-16.57
PTF09sh	36.10	-19.36	-20.18	-20.68	-20.92	-20.86	-19.92
PTF09sk	35.97	-17.38	-18.13	-18.36	-18.55	-18.62	-17.88
PTF09t	36.18	-19.30	-20.08	-20.38	-20.54	-20.63	-19.84
PTF09tm	35.94	-18.78	-20.05	-20.69	-21.03	-21.30	-19.69
PTF09uj	37.33	-18.80	-19.68	-20.07	-20.25	-20.28	-19.42
PTF10bau	35.28	-20.08	-21.00	-21.50	-21.71	-21.92	-20.71
PTF10bfz	39.27	-16.29	-17.09	-17.34	-16.87	-15.52	-16.82
PTF10bgl	35.59	-20.67	-21.62	-22.00	-22.20	-22.33	-21.34
PTF10bhu	36.00	-18.12	-19.03	-19.42	-19.60	-19.79	-18.75
PTF10bip	36.78	-16.72	-17.87	-18.10	-18.32	-18.51	-17.56
PTF10bzf	36.73	-16.81	-17.21	-17.77	-17.94	-18.22	-16.97
PTF10cd	36.52	-17.11	-17.71	-18.13	-17.81	-17.94	-17.51
PTF10con	35.81	-18.55	-19.41	-20.35	-21.07	-20.77	-19.08
PTF10cqh	36.29	-20.13	-21.25	-21.81	-22.09	-22.31	-20.93
PTF10cwx	37.59	-18.12	-18.79	-19.05	-19.18	-19.32	-18.53
PTF10cxq	36.60	-17.96	-18.67	-18.86	-18.98	-18.99	-18.43
PTF10cxx	35.87	-18.40	-19.65	-20.26	-20.56	-20.86	-19.30
PTF10czn	36.50	-20.23	-21.33	-21.78	-22.00	-22.13	-21.02
PTF10dk	37.62	-14.43	-15.89	-16.37	-16.35	-16.34	-15.63
PTF10dvb	35.00	-19.50	-20.40	-20.83	-21.02	-21.22	-20.11
PTF10hv	36.81	-18.56	-19.56	-19.88	-20.12	-20.21	-19.27
PTF10in	37.50	-15.08	-16.08	-16.27	-16.73	-16.36	-15.80
PTF10s	36.78	-18.00	-18.94	-19.36	-19.56	-19.71	-18.66
PTF10ts	36.55	-18.52	-19.47	-19.92	-20.16	-20.28	-19.18
PTF10u	39.27	-15.69	-16.48	-17.68	-17.96	-18.38	-16.38

^a Assuming $H_0 = 70$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$

^b Magnitudes are corrected for galactic extinction but not intrinsic extinction.

Table 5
Host galaxy properties fit from SDSS photometry

SN Name	type	M log M _⊙	SFR (FAST) log M _⊙ /yr	SFR (u) log M _⊙ /yr	SSFR log yr ⁻¹	Age log yr
PTF09aux	Ic/Ia	10.43 ^{+0.03} _{-0.07}	-0.59 ^{+0.43} _{-0.00}	-0.06	-11.03 ^{+0.45} _{-0.00}	9.70 ^{+0.02} _{-0.16}
PTF09awk	Ib	9.45 ^{+0.18} _{-0.14}	0.61 ^{+0.35} _{-0.73}	0.44	-8.85 ^{+0.47} _{-0.83}	8.80 ^{+0.56} _{-0.42}
PTF09axc	II	10.33 ^{+0.01} _{-0.09}	-0.25 ^{+0.33} _{-0.00}	0.04	-10.58 ^{+0.36} _{-0.00}	9.60 ^{+0.01} _{-0.14}
PTF09axi	II	9.35 ^{+0.09} _{-0.04}	-0.33 ^{+0.03} _{-0.16}	-0.31	-9.68 ^{+0.00} _{-0.24}	9.30 ^{+0.11} _{-0.06}
PTF09bce	II	10.68 ^{+0.08} _{-0.09}	0.11 ^{+0.83} _{-0.95}	0.36	-10.58 ^{+0.90} _{-1.01}	9.60 ^{+0.20} _{-0.37}
PTF09bgf	II	8.59 ^{+0.06} _{-0.19}	-0.88 ^{+0.74} _{-0.00}	-0.80	-9.47 ^{+0.87} _{-0.00}	9.20 ^{+0.06} _{-0.68}
PTF09bw	II	9.75 ^{+0.02} _{-0.15}	-0.83 ^{+0.34} _{-0.00}	-0.77	-10.58 ^{+0.36} _{-0.00}	9.60 ^{+0.02} _{-0.19}
PTF09cjg	II	10.84 ^{+0.05} _{-0.14}	0.62 ^{+0.98} _{-0.37}	0.71	-10.22 ^{+1.09} _{-0.36}	9.50 ^{+0.15} _{-0.54}
PTF09ct	II	10.00 ^{+0.10} _{-0.19}	-0.22 ^{+1.46} _{-0.27}	-0.00	-10.22 ^{+1.62} _{-0.36}	9.50 ^{+0.10} _{-0.95}
PTF09cu	II	10.48 ^{+0.09} _{-0.19}	0.81 ^{+0.89} _{-0.51}	0.77	-9.68 ^{+1.08} _{-0.54}	9.30 ^{+0.22} _{-0.71}
PTF09cvi	II	7.07 ^{+0.17} _{-0.15}	< -2.06 ^{+0.38} _{-0.42}	-1.63	-9.13 ^{+0.41} _{-0.55}	9.00 ^{+0.34} _{-0.34}
PTF09dah	IIB	8.50 ^{+0.38} _{-0.13}	1.70 ^{+0.02} _{-1.72}	0.83	-6.80 ^{+0.00} _{-2.05}	6.80 ^{+2.10} _{-0.08}
PTF09dfk	Ib	8.77 ^{+0.07} _{-0.14}	-0.91 ^{+0.72} _{-0.24}	-0.80	-9.68 ^{+0.83} _{-0.24}	9.30 ^{+0.13} _{-0.52}
PTF09djl	II	10.22 ^{+0.09} _{-0.06}	-0.35 ^{+0.06} _{-0.36}	-0.16	-10.58 ^{+0.00} _{-0.45}	9.60 ^{+0.10} _{-0.09}
PTF09dra	II	10.34 ^{+0.22} _{-0.14}	1.62 ^{+0.32} _{-1.28}	1.33	-8.72 ^{+0.45} _{-1.50}	8.70 ^{+0.80} _{-0.41}
PTF09due	II	10.51 ^{+0.07} _{-0.18}	0.83 ^{+0.82} _{-0.25}	0.79	-9.68 ^{+0.96} _{-0.24}	9.30 ^{+0.14} _{-0.64}
PTF09dxv	IIB	9.93 ^{+0.19} _{-0.11}	1.20 ^{+0.26} _{-1.01}	0.95	-8.72 ^{+0.34} _{-1.20}	8.70 ^{+0.70} _{-0.31}
PTF09dzt	Ic	9.48 ^{+0.36} _{-0.10}	2.58 ^{+0.13} _{-1.24}	1.70	-6.89 ^{+0.09} _{-1.60}	6.90 ^{+1.61} _{-0.12}
PTF09ebq	II	9.59 ^{+0.24} _{-0.15}	0.99 ^{+0.30} _{-1.11}	0.74	-8.60 ^{+0.43} _{-1.32}	8.60 ^{+0.81} _{-0.41}
PTF09ecm	II	9.83 ^{+0.06} _{-0.09}	0.15 ^{+0.50} _{-0.19}	0.18	-9.68 ^{+0.55} _{-0.24}	9.30 ^{+0.11} _{-0.36}
PTF09ejz	Ic/Ia	10.79 ^{+0.05} _{-0.08}	0.22 ^{+0.85} _{-0.06}	0.50	-10.58 ^{+0.90} _{-0.00}	9.60 ^{+0.05} _{-0.33}
PTF09fae	IIB	8.03 ^{+0.23} _{-0.13}	0.56 ^{+0.33} _{-0.41}	0.06	-7.47 ^{+0.38} _{-0.59}	7.50 ^{+0.63} _{-0.42}
PTF09fbf	II	10.08 ^{+0.10} _{-0.13}	0.61 ^{+0.63} _{-0.40}	0.54	-9.47 ^{+0.75} _{-0.45}	9.20 ^{+0.22} _{-0.51}
PTF09fmk	II	10.12 ^{+0.23} _{-0.16}	1.52 ^{+0.31} _{-1.14}	1.22	-8.60 ^{+0.43} _{-1.32}	8.60 ^{+0.84} _{-0.44}
PTF09foy	II	10.30 ^{+0.07} _{-0.11}	0.38 ^{+0.70} _{-0.26}	0.44	-9.92 ^{+0.79} _{-0.30}	9.40 ^{+0.11} _{-0.40}
PTF09fqa	II	9.97 ^{+0.07} _{-0.10}	0.05 ^{+0.56} _{-0.23}	0.12	-9.92 ^{+0.63} _{-0.30}	9.40 ^{+0.10} _{-0.36}
PTF09fsr	Ib	10.85 ^{+0.03} _{-0.02}	0.27 ^{+0.03} _{-0.02}	0.50	-10.58 ^{+0.00} _{-0.00}	9.60 ^{+0.01} _{-0.08}
PTF09g	II	9.85 ^{+0.05} _{-0.16}	0.17 ^{+0.82} _{-0.02}	0.19	-9.68 ^{+0.96} _{-0.00}	9.30 ^{+0.04} _{-0.61}
PTF09gof	II	10.17 ^{+0.03} _{-0.10}	0.25 ^{+0.40} _{-0.00}	0.35	-9.92 ^{+0.45} _{-0.00}	9.40 ^{+0.01} _{-0.25}
PTF09gtt	II	9.03 ^{+0.13} _{-0.20}	0.18 ^{+0.43} _{-0.73}	0.03	-8.85 ^{+0.58} _{-0.83}	8.80 ^{+0.51} _{-0.55}
PTF09hdo	II	10.80 ^{+0.07} _{-0.14}	0.88 ^{+0.83} _{-0.65}	0.87	-9.92 ^{+0.94} _{-0.66}	9.40 ^{+0.22} _{-0.58}
PTF09hgz	II	10.42 ^{+0.09} _{-0.19}	0.50 ^{+1.02} _{-0.65}	0.51	-9.92 ^{+1.20} _{-0.66}	9.40 ^{+0.28} _{-0.70}
PTF09iex	II	8.00 ^{+0.21} _{-0.41}	-0.27 ^{+1.67} _{-0.53}	-0.48	-8.27 ^{+1.67} _{-0.71}	8.30 ^{+0.61} _{-1.71}
PTF09ige	II	9.83 ^{+0.04} _{-0.09}	0.15 ^{+0.30} _{-0.01}	0.18	-9.68 ^{+0.55} _{-0.00}	9.30 ^{+0.03} _{-0.32}
PTF09igz	II	9.45 ^{+0.10} _{-0.58}	-0.23 ^{+2.35} _{-0.15}	-0.14	-9.68 ^{+2.88} _{-0.24}	9.30 ^{+0.10} _{-2.51}
PTF09ism	II	9.26 ^{+0.09} _{-0.14}	-0.21 ^{+0.65} _{-0.15}	-0.19	-9.47 ^{+0.75} _{-0.21}	9.20 ^{+0.13} _{-0.54}
PTF09ps	Ic	8.86 ^{+0.54} _{-0.11}	2.06 ^{+0.15} _{-2.37}	1.16	-6.80 ^{+0.10} _{-2.88}	6.80 ^{+2.52} _{-0.12}
PTF09q	Ic	10.77 ^{+0.05} _{-0.14}	0.55 ^{+1.00} _{-0.35}	0.67	-10.22 ^{+1.09} _{-0.36}	9.50 ^{+0.11} _{-0.55}
PTF09r	II	9.14 ^{+0.05} _{-0.09}	-1.44 ^{+0.82} _{-0.03}	-1.03	-10.58 ^{+0.90} _{-0.00}	9.60 ^{+0.05} _{-0.30}
PTF09sh	II	10.05 ^{+0.08} _{-0.07}	0.37 ^{+0.35} _{-0.18}	0.37	-9.68 ^{+0.39} _{-0.24}	9.30 ^{+0.11} _{-0.24}
PTF09sk	Ic-BL	8.99 ^{+0.08} _{-0.42}	-0.30 ^{+2.10} _{-0.17}	-0.31	-9.29 ^{+2.49} _{-0.18}	9.10 ^{+0.17} _{-2.31}
PTF09t	II	9.83 ^{+0.08} _{-0.14}	0.36 ^{+0.64} _{-0.15}	0.33	-9.47 ^{+0.75} _{-0.21}	9.20 ^{+0.11} _{-0.54}
PTF09tm	II	10.42 ^{+0.08} _{-0.15}	0.50 ^{+0.83} _{-0.66}	0.52	-9.92 ^{+0.94} _{-0.66}	9.40 ^{+0.25} _{-0.57}
PTF09uj	II	9.79 ^{+0.08} _{-0.05}	0.12 ^{+0.21} _{-0.17}	0.15	-9.68 ^{+0.21} _{-0.24}	9.30 ^{+0.10} _{-0.19}
PTF10bau	II	10.47 ^{+0.07} _{-0.24}	0.79 ^{+0.99} _{-0.25}	0.75	-9.68 ^{+1.19} _{-0.24}	9.30 ^{+0.16} _{-0.82}
PTF10bfz	Ic-BL	8.34 ^{+0.20} _{-0.53}	-0.79 ^{+3.08} _{-0.14}	-0.82	-9.13 ^{+3.03} _{-0.34}	9.00 ^{+0.21} _{-3.00}
PTF10bgl	II	10.61 ^{+0.07} _{-0.11}	0.93 ^{+0.62} _{-0.20}	0.87	-9.68 ^{+0.70} _{-0.24}	9.30 ^{+0.11} _{-0.45}
PTF10bhu	Ic	9.59 ^{+0.07} _{-0.18}	-0.09 ^{+0.82} _{-0.21}	-0.04	-9.68 ^{+0.96} _{-0.24}	9.30 ^{+0.12} _{-0.64}
PTF10bip	Ic	9.01 ^{+0.13} _{-0.08}	-0.12 ^{+0.24} _{-0.69}	-0.23	-9.13 ^{+0.28} _{-0.79}	9.00 ^{+0.41} _{-0.23}
PTF10bzf	Ic-BL	8.23 ^{+0.25} _{-0.07}	1.14 ^{+0.29} _{-0.58}	0.52	-7.09 ^{+0.20} _{-0.77}	7.10 ^{+0.89} _{-0.21}
PTF10cd	II	8.61 ^{+0.10} _{-0.32}	-0.52 ^{+2.17} _{-0.08}	-0.53	-9.13 ^{+2.43} _{-0.16}	9.00 ^{+0.12} _{-2.32}
PTF10con	II	10.29 ^{+0.07} _{-0.49}	0.36 ^{+1.42} _{-0.62}	0.51	-9.92 ^{+1.86} _{-0.66}	9.40 ^{+0.21} _{-1.34}
PTF10cqh	II	10.76 ^{+0.06} _{-0.15}	0.83 ^{+0.83} _{-0.31}	0.84	-9.92 ^{+0.94} _{-0.30}	9.40 ^{+0.16} _{-0.53}
PTF10cwz	II	9.10 ^{+0.17} _{-0.41}	0.61 ^{+1.59} _{-0.83}	0.38	-8.49 ^{+1.79} _{-0.98}	8.50 ^{+0.70} _{-1.83}
PTF10cxq	II	9.10 ^{+0.09} _{-0.12}	-0.18 ^{+0.56} _{-0.11}	-0.20	-9.29 ^{+0.69} _{-0.18}	9.10 ^{+0.11} _{-0.50}
PTF10czz	II	10.22 ^{+0.08} _{-0.14}	0.30 ^{+0.82} _{-0.66}	0.34	-9.92 ^{+0.94} _{-0.66}	9.40 ^{+0.22} _{-0.53}
PTF10czn	II	10.63 ^{+0.07} _{-0.07}	0.71 ^{+0.40} _{-0.24}	0.71	-9.92 ^{+0.45} _{-0.30}	9.40 ^{+0.11} _{-0.23}

Table 5 — *Continued*

SN Name	type	M log M _⊙	SFR (FAST) log M _⊙ /yr	SFR (u) log M _⊙ /yr	SSFR log yr ⁻¹	Age log yr
PTF10dk	II	8.36 ^{+0.17} _{-0.62}	-1.56 ^{+2.50} _{-0.15}	-1.51	-9.92 ^{+3.12} _{-0.30}	9.40 ^{+0.12} _{-2.60}
PTF10dvb	II	10.13 ^{+0.11} _{-0.20}	0.66 ^{+0.80} _{-0.39}	0.59	-9.47 ^{+0.98} _{-0.45}	9.20 ^{+0.22} _{-0.70}
PTF10hv	II	9.82 ^{+0.04} _{-0.13}	-0.11 ^{+0.72} _{-0.00}	-0.01	-9.92 ^{+0.79} _{-0.00}	9.40 ^{+0.01} _{-0.48}
PTF10in	IIb	8.19 ^{+0.29} _{-0.60}	-0.42 ^{+1.42} _{-1.09}	-0.59	-8.60 ^{+1.80} _{-1.32}	8.60 ^{+0.83} _{-1.88}
PTF10s	II	9.61 ^{+0.05} _{-0.13}	-0.31 ^{+0.83} _{-0.02}	-0.18	-9.92 ^{+0.94} _{-0.00}	9.40 ^{+0.03} _{-0.52}
PTF10ts	II	9.86 ^{+0.04} _{-0.12}	-0.06 ^{+0.81} _{-0.05}	0.04	-9.92 ^{+0.94} _{-0.00}	9.40 ^{+0.04} _{-0.50}
PTF10u	II	9.72 ^{+0.21} _{-0.25}	-3.47 ^{+2.58} _{-0.13}	-0.86	-13.18 ^{+2.60} _{-0.00}	10.00 ^{+0.00} _{-0.46}